Mervyn Siberry

INSTRUMENTS OF FLIGHT

A GUIDE TO THE PILOT'S FLIGHT PANEL OF A MODERN AIRLINER

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DAVID & CHARLES

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In the past decade, aircraft instruments have largely relinquished their individual roles to become part of integrated systems tied to navigation and automatic flight control. Despite the apparent sophistication, the object of this development has been to simplify the pilot's task and reduce his workload.

This book takes a close-up look at the instruments and systems of today. It traces a little of what led up to the present instrument displays, explains the purpose and operational principles of individual instruments, outlines the various information requirements during phases of a typical flight, and describes how the instruments acquire and display this information.

Instruments and systems covered include Air-operated Indicators, Gyroscopic Instruments, Flight Directors, Autopilots, Radio and Inertial Navigation Systems and Weather Radar. A final chapter written by a senior BEA captain describes the techniques of automatic landings and poses the question 'When will human pilots be redundant?'

Illustrated by thirty-eight explanatory line drawings and eleven photographs, this is both a clear and basic introduction to a fascinating subject and an ideal guide to the intimidating array of dials confronting the modern airline pilot.

THE AUTHOR

Mr K. M. Siberry's sixteen years experience in the field of avionics has included eight with Hawker Siddeley Aviation instructing pilots and engineers in the use of instruments, flight systems and autopilots. On subsequently joining the British Aircraft Corporation, he was engaged on Concorde instrumentation during 1971 and is now with Court Line Aviation, after having completed a Tristar familiarisation course with the Lockheed Aircraft Corporation in California.

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MERVYN SIBERRY

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CONTENTS

		Page
	LIST OF ILLUSTRATIONS	7
	INTRODUCTION	9
1	Level Flight	21
2	Turn and Slip	29
3	Holding Course	37
4	Flying Speed	47
5	Measuring Altitude	56
6	Rate of Climb	65
7	Mach Number	70
8	The Flight Director	78
9	Engage Autopilot	87
10	Weather Radar	96
11	Inertial Navigation	105
12	The Autoland Age: *by Capt R. E. Gillman,* DFC, DFM, FRMetS	110
	ACKNOWLEDGEMENTS	121
	INDEX	123

LIST OF ILLUSTRATIONS

PLATES

	Page
Simple flight instrument panel used for delivery on HS125 Executive aircraft (*Hawker Siddeley*)	17
Integrated flight system instruments on HS125 (*Hawker Siddeley*)	18
Complete flight instrument panel layout of HS125 (*Hawker Siddeley*)	35
Captain's panel on Trident 2 (*British European Airways*)	36
Co-pilot's panel on BEA Super One-Eleven (*British European Airways*)	36
Flight detector system of the future (*Sperry*)	53
Sperry flight system instruments for DC-10 wide-body jet (*Sperry*)	53
Lawrence Sperry's award-winning autopilot fitted in a Curtiss seaplane (*Sperry*)	54
Gyro unit at the heart of the Smiths SEP2 autopilot (*Smiths Industries*)	71
Flight controller of the Smiths flight control system fitted on Trident aircraft (*Smiths Industries*)	71
Inertial navigation control and display unit on BOAC jumbo jet	72

LINE ILLUSTRATIONS

FIGURE		Page
1	Aircraft sensitive altimeter (*Smiths Industries*)	10
2	Basic-Six instrument panel layout	12
3	Basic-T instrument panel layout	12

FIGURE		Page
4	Captain's instrument panel on Lockheed Tristar (*Court Line*)	14
5	Captain's instrument panel on Concorde (*BAC*)	15
6	Director horizon (*Smiths Industries*)	22
7	Artificial horizon gyro mechanism (*Jim McCartney*)	27
8	Turn and slip indicator (*Smiths Industries*)	30
9	Turn and slip gyro mechanism (*Smiths Industries*)	33
10	Horizontal situation indicator (*Smiths Industries*)	38
11	Directional gyro (*Jim McCartney*)	40
12	Radio magnetic indicator (*Jim McCartney*)	42
13	VHF omni-range beacon (VOR) (*Jim McCartney*)	44
14	Standby magnetic compass (*Smiths Industries*)	45
15	Airspeed indicator (*Smiths Industries*)	48
16	Principle of the airspeed indicator (*Smiths Industries*)	50
17	Digital altimeter (*Smiths Industries*)	57
18	Altimeter capsule mechanism (*Smiths Industries*)	58
19	Multi-pointer altimeter (*Smiths Industries*)	60
20	Multi-pointer altimeter with 10,000ft pointer obscured (*Smiths Industries*)	61
21	Modern multi-pointer altimeter (*Smiths Industries*)	62
22	Vertical speed indicator (*Smiths Industries*)	66
23	Vertical speed indicator mechanism (*Jim McCartney*)	68
24	Machmeter (*Smiths Industries*)	73
25	Machmeter mechanism (*Jim McCartney*)	74
26	Mach/airspeed indicator (*Smiths Industries*)	76
27	Director horizon (*Smiths Industries*)	79
28	Zero-reader flight direction indicator (*Sperry*)	83
29	Instrument landing system (ILS) localiser approach	85
30	Autopilot roll channel (*Smiths Industries*)	89
31	Autopilot controller (*Hawker Siddeley*)	92
32	Controller on Tristar and Concorde (*Court Line and BAC*)	94
33	Weather radar indicator and control panel (*MEL*)	97
34	Cloud displays on radar screens (*MEL*)	101
35	Radar antenna in nose of Tristar (*Court Line*)	103
36	Inertial navigation control and display unit (*Jim McCartney*)	107
37	Automatic landing diagram (*Smiths Industries*)	115

INTRODUCTION

In the earliest days of controlled flight the pilot of a flying machine relied on a clear view of the earth below to enable him to perform flight manoeuvres. Inevitably, his flying was thus restricted to clear weather and daylight hours, but at least his field of view was excellent, seated as he usually was in the open air and at the forward edge of the wings. To some extent, he had additional information inputs from the machine itself via 'the seat of his pants'—inputs which were not entirely reliable until aviation was quite advanced and he had learnt the importance of strapping himself into the seat. Navigation was of the simplest kind requiring only a knowledge of the locality and the ability to steer from landmark to landmark by following surface features such as roads, railways, canals and rivers.

One obvious and unfortunate difference between the aeroplane and all other modes of transport is the necessity to maintain speed between possible landing places to prevent it from falling out of the sky. The first practical airspeed indicator, invented by a Frenchman, Capt A. Étevé, was tested in 1911, nearly eight years after the first powered sustained flights by the Wright brothers. A magnetic compass was a useful addition to a craft free to travel in the air and, later still, the altimeter, which was an aneroid barometer to measure aircraft height. The purpose of these instruments was to indicate with a greater degree of accuracy information which the pilot could only estimate by visual clues from his environment.

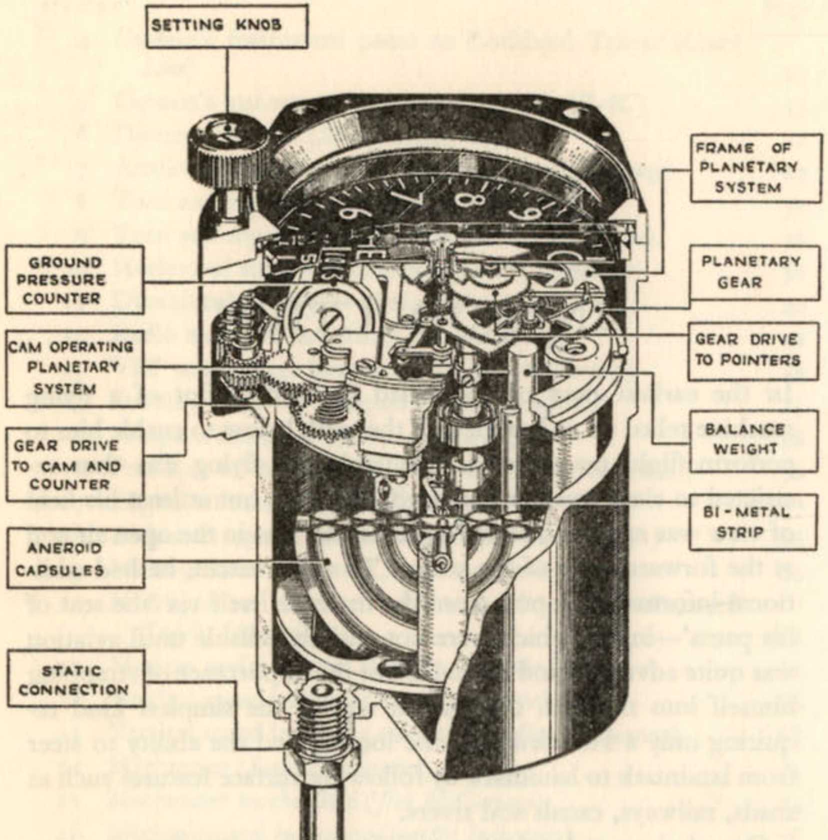


Figure 1 Aircraft sensitive altimeter—a typical flight instrument in which small pressure changes are sensed by aneroid capsules which drive the pointers through gearing

Night flying was first accomplished in 1910 and was seriously investigated as a regular practice at Hendon, near London, in 1913. In those years, though instruments were helpful, they were not the primary means by which aircraft were guided during night flights. The pilots relied on their night vision assisted by moonlight and the many lights visible on the ground below. They used something of their sense of balance and watched the movement of their wing-tips past the stars. Later, when illuminated instruments were used, it was still advisable to maintain good visual contact with the outside world, as discovered by one midnight flyer who landed unexpectedly while his illuminated height indicator informed him that he was still 300ft up in the air!

Instruments using the properties of the gyroscope were developed by Lawrence Sperry in the United States and were adopted as standard additions to the group. Instrument flying became acceptable by the end of World War I, and in the following decade expanded successfully. In 1929, Lt James Doolittle, in a biplane fitted with Sperry's gyro horizon and directional gyro, was able 'to take-off, fly a specific course and land without reference to the earth'. From 1930 such instruments, together with vertical speed indicators and more sensitive altimeters, were standard equipment on most types of aircraft.

These indicators form a group quite distinct from the many other indicators showing oil pressures, fuel quantities, revolutions per minute, temperature and so on. This book deals only with the flight instruments, which are a group of indicators peculiar to this mode of transport alone. A typical self-contained instrument is shown in cut-away view in Fig 1. It is a pressure-operated altimeter which measures the aircraft's height in the atmosphere. The mechanism senses air pressure applied to the static connection by means of aneroid capsules and transmits capsule movement to the pointers through planetary gearing. Variations of temperature are compensated by the influence of the bi-metal strip, and an adjustment for changes in atmospheric pressure can be made by means of the setting knob. This knob rotates the cam to alter the gearing movement and also moves

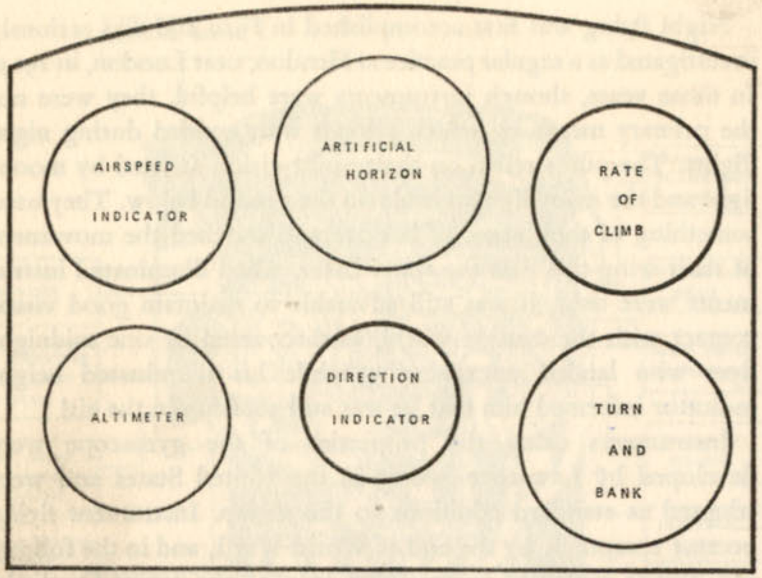


Figure 2 Basic-Six instrument panel layout. A standard arrangement of flight instruments for many years until replaced by the Basic-T layout shown in Fig 3

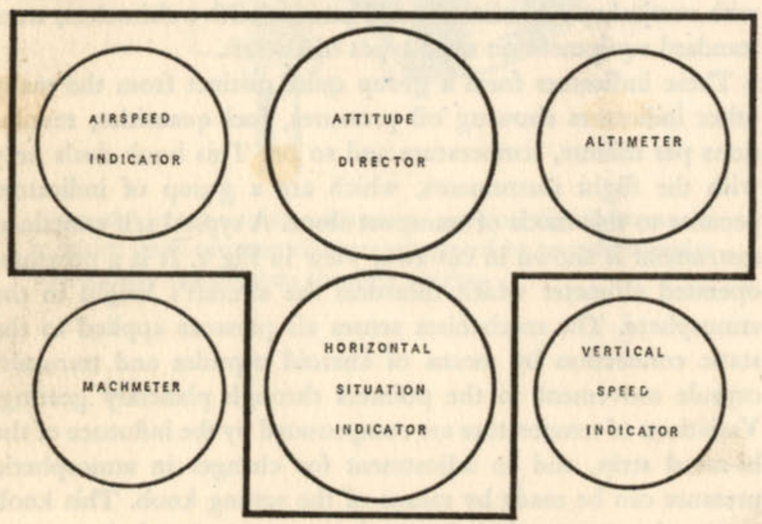


Figure 3 Basic-T instrument panel layout. The standard arrangement of flight instruments on most transport aircraft

a set of ground-pressure counters to show the change of setting.

The dial and the entire mechanism are housed in a robust moulded plastic case with a strong glass front sealed by a rubber ring. The main moving parts are balanced by weights to prevent aircraft accelerations from affecting the indication. The design must ensure that the normal vibrations which it will encounter will not have an adverse affect, and it must be capable of withstanding heavy shocks during landing and taxi-ing. Instruments must also function satisfactorily and be free from corrosion during and after severe climatic testing, including temperature, pressure and humidity changes. Another very important constraint on the design is that instruments for aircraft must be of the minimum weight consistent with reliability.

The basic six flight instruments covering the most vital requirements of the pilot were capable of a variety of displays. A great improvement in presentation was achieved by grouping them in a standard pattern in front of the pilot as shown in Fig 2. To ensure that all six displays were monitored by the pilot, various scanning techniques were developed by which each dial was viewed as part of a predetermined sequence and no one was ignored. Considerable skill is required to view and correct the wanderings of six displays where the changing of any one may affect one or more others. Later developments of instruments combined two or more displays in one dial, thus reducing the number of scanning operations for a given information intake. The Basic-Six grouping was changed to the Basic-T grouping, usually depicted by a white border line painted on the panel as shown in Fig 3. Within the T are all the most vital displays including radio navigation inputs not so prominent in the days of the basic six. Scanning techniques for this grouping do, of course, include other instruments outside the T.

Automatic control of aircraft flight was achieved by Sperry in 1912 and demonstrated by him in a competition for 'a stable aeroplane' two years later. Automatic pilots of later development used inputs from the flight instruments to introduce navigational guidance features in addition to the basic stabilisation role. Thus,

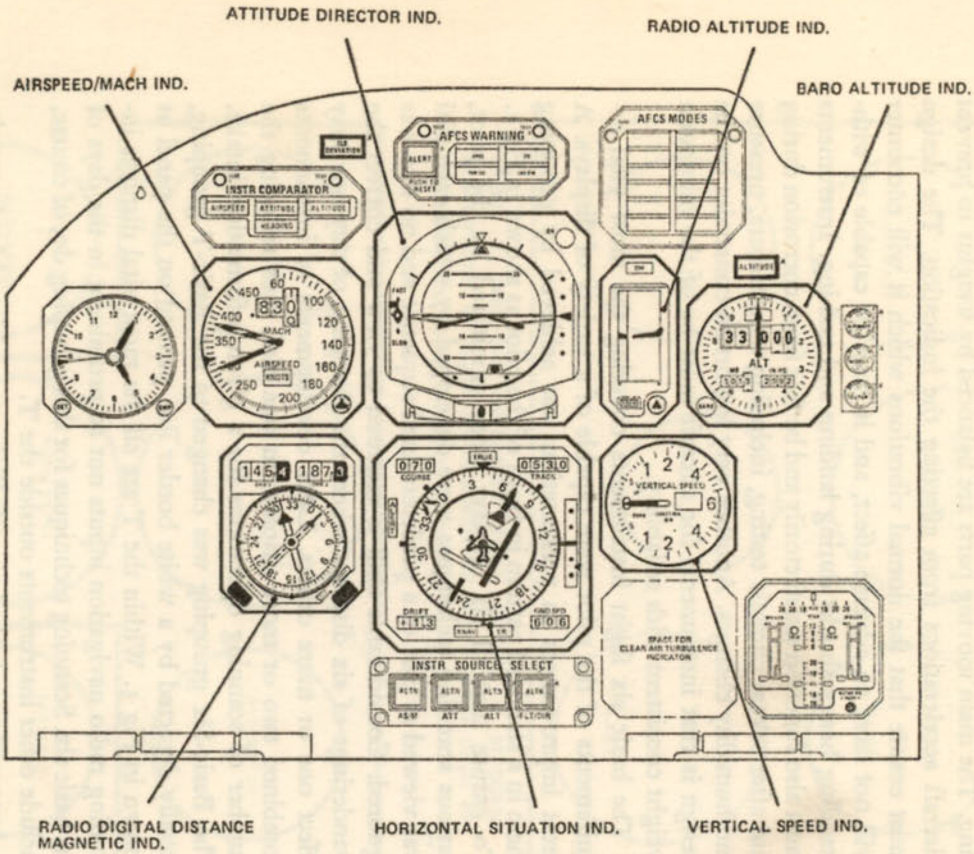


Figure 4 Captain's instrument panel on the Lockheed Tristar, the first aircraft to begin service with the capability of fully automatic landing

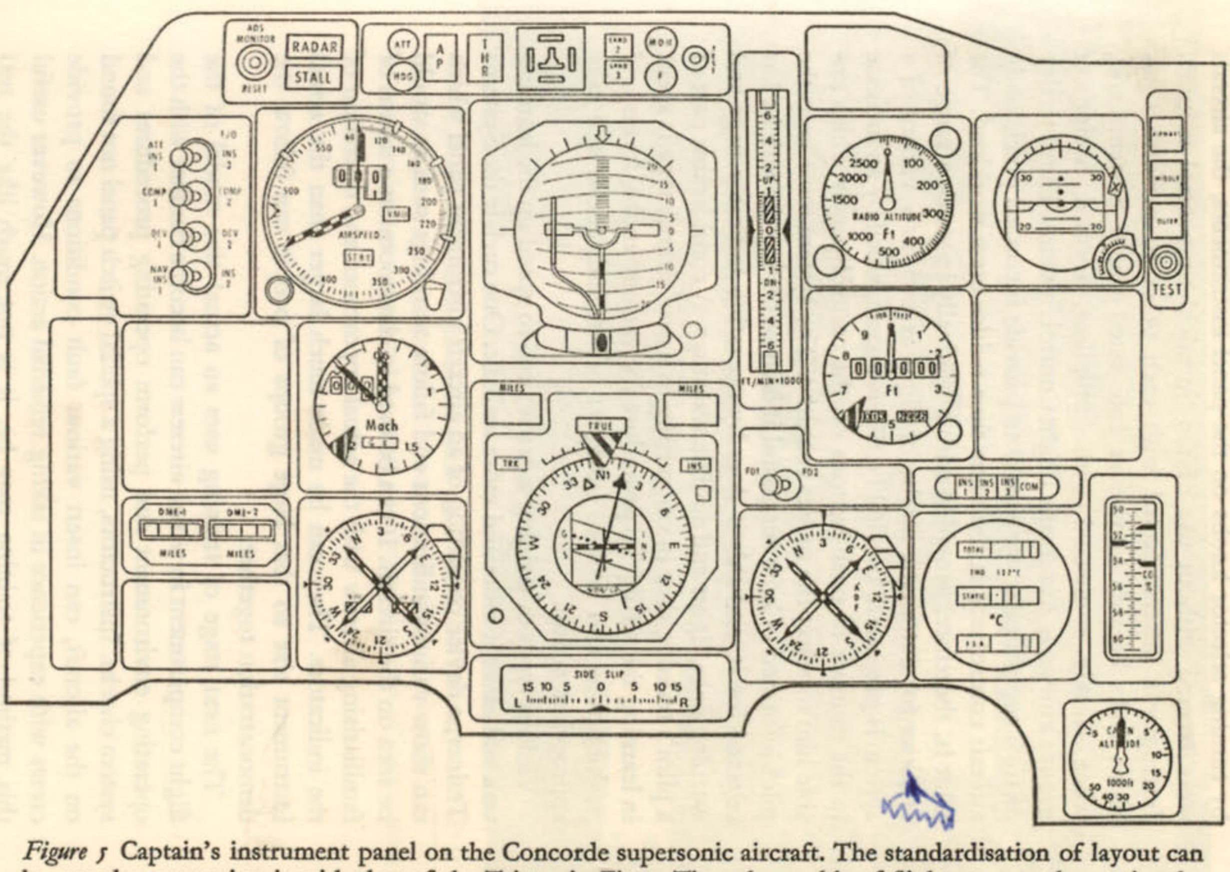
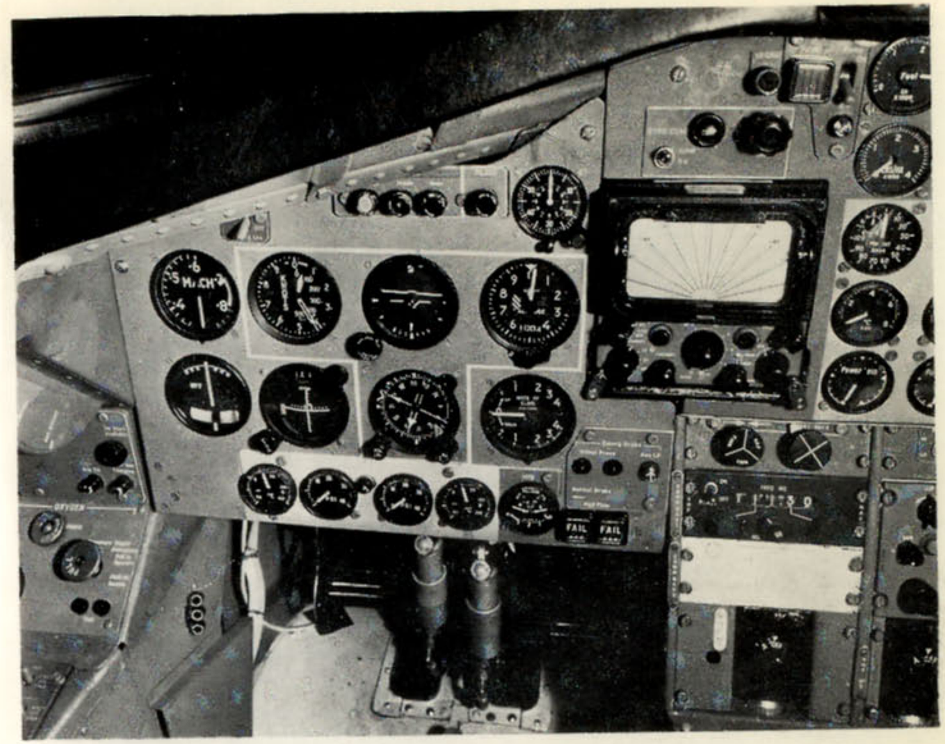


Figure 5 Captain's instrument panel on the Concorde supersonic aircraft. The standardisation of layout can be seen by comparing it with that of the Tristar in Fig 4. Though capable of flight at more than twice the speed of sound, Concorde relies on similar instrumentation to that of sub-sonic types

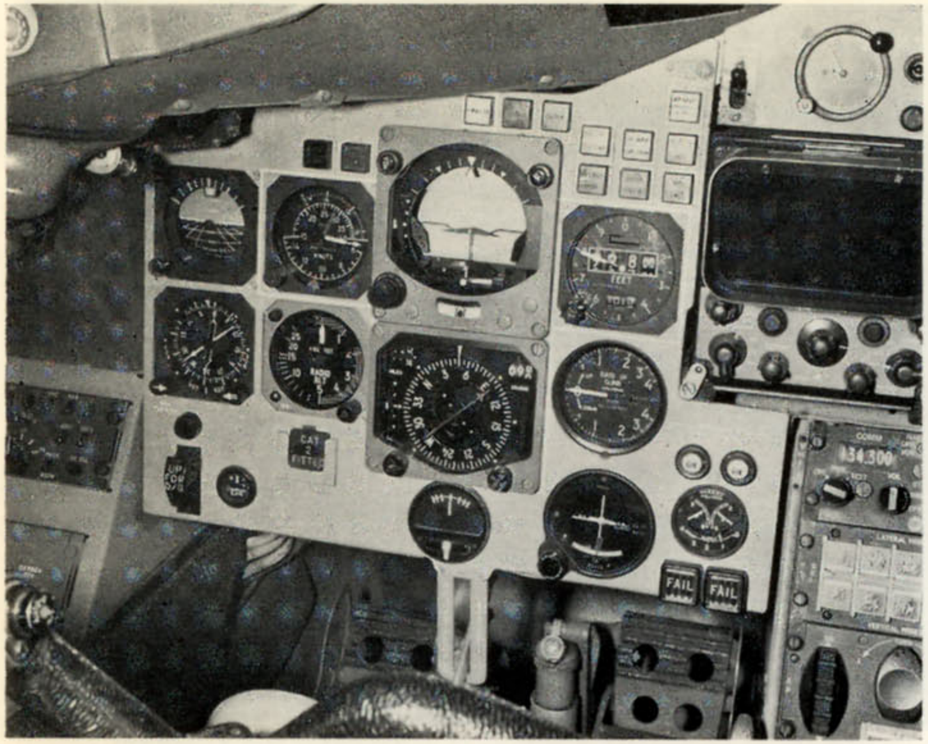
by turning selector knobs on the panel instruments, the aircraft were steered without use of the 'joystick' or control column. Instruments interconnected with each other to perform combined tasks became known as Integrated Flight Systems and, when closely connected with autopilots, formed equipment groups known as Automatic Flight Control Systems. The objective of such sophisticated systems is to provide increased precision in aircraft control and at the same time reduce crew workload. The pilot is, therefore, provided with a gradually increasing range of facilities for automatic modes of flight as each new variant of a system is produced. Inevitably, this is accompanied by an increase in the number of push-buttons on the control panels which enable him to select the modes required. The system must keep the pilot informed of how successful it is in achieving the task he has selected for it, and this it does by operating indicator flags and warning flags, lights and audible warnings. A considerable part of a pilot's training time in converting to a new aircraft type is spent in learning the setting up procedure for various knobs, levers and push-buttons and how to interpret failure indications and take appropriate action.

Various types of training aids are used to speed up the learning task and make it more and more realistic. One such is the Systems Trainer, a device consisting of an aircraft instrument panel which can show various indications and failure warnings such as would be seen on the aircraft. It can be used in classrooms as a means of familiarising aircrew with the actual appearance and operation of the indicators. They can be made much larger than the actual instrument size so that large groups of people can follow the demonstration together.

The next stage of training uses an actual size model of the flight compartment in which aircrew can become familiar with the operating environment and perform operating procedures and system checks. Instructors, using a special switch panel not found on the aircraft, can insert various fault conditions to provide crews with experience in taking remedial action. However useful this method of training may be, it is not much like the real



Page 17 Simple flight instrument panel used for delivery of HS125 Executive aircraft to overseas customers. On arrival, this panel will be replaced by one containing a more sophisticated group of instruments



Page 18 Integrated flight system instruments on the captain's panel of a HS125 Executive aircraft. This system is very similar to that on the largest passenger airliners

experience of operating the aircraft in flight conditions. For that degree of realism, only the actual aircraft or a full Flight Simulator will suffice.

The Flight Simulator is a copy of the nose section of the aircraft, supported on hydraulic jacks, capable of simulating all the sensations of movement which the real aircraft could provide. The instruments used in simulators are either actual aircraft instruments or completely authentic-looking replicas. All are driven by a computer housed in a room remote from the moving nose section. Any particular flight situation or manoeuvre as shown on the instruments is accompanied by the appropriate physical sensation of movement. For example, centrifugal force can by simulated by tipping the nose section sideways without the instruments displaying any change from level. The results are completely convincing. The rumble of the wheels on the runway can be felt, also the bumps of various amounts of air turbulence and the differences of aircraft behaviour with different aircraft loads.

Through the windshield, the 'pilots' can see a visual display such as they would see from the flight deck of the real aircraft and, of course, such a display must correspond to the indications of the panel instruments. It must appear so that the ground is as far away as the altimeter indicates it to be. The scene should move at a speed corresponding to the airspeed indicator and the altimeter and move appropriately with the manoeuvres performed by the pilot at the controls. In fact, there would appear to be no element of the total flight experience which the simulation engineers cannot reproduce. When incorrect operation results in a situation which would produce a crash of the aircraft, the simulator stops at the point of impact, freezing all instruments and visual displays in position. This enables the instructor to conduct a 'post-mortem' with the crew to determine how such a situation arose.

Each new aircraft type, when it is introduced to the operator, brings with it the need for re-training in the differences to be seen on its instrument panels. Although the basic methods of information display are standardised, progress in instrument design pro-

duces differences of display which must be fully understood by the pilot. An impression of both the similarities and differences of panel layout can be gained by comparing a Tristar captain's panel in Fig 4 with that of a Concorde panel in Fig 5. Both layouts conform to the Basic-T pattern, with speed at the upper left and altitude at the upper right. Top centre shows a symbolic aeroplane outlined against the horizon and, below this, an aircraft viewed from above in the centre of a compass card. Tristar has a vertical moving-tape indicator for radio altitude indication, while Concorde has a similar indicator in the same position but indicating vertical speed.

These flight instrument panels probably represent the limits of development in electro-mechanical devices for information display. The techniques which follow in later designs incorporate electronically generated displays using cathode-ray tubes. A typical display of that kind is shown in the illustration on p 53.

Each of the following chapters of this book describes a particular instrument or system, and together they should permit an appreciation of the typical panels illustrated by the photographic plates.

I

LEVEL FLIGHT

ENTERING cloud. The sky is completely overcast and the pilot, staring ahead through his heated windscreen, can see nothing but a greyish whiteness, featureless and dull. This cloud cover is several thousand feet deep but eventually the aircraft will break out on top and leave it far below; a level sea of sunlit cotton wool dazzling in its brightness.

Meanwhile, the pilot is entirely dependent on instruments for clues as to the progress he is making and, in a modern airliner, these are grouped in a panel facing the left-hand seat normally occupied by the captain. On this panel, known as the captain's panel, are grouped the most vital indications essential to the control of aircraft manoeuvres. The first officer or co-pilot, sitting on the right-hand side of the flightdeck, has a similar panel of instruments, most of them identical to those on the left.

The most vital piece of information displayed at the centre of attention in these groups is simply a statement of 'which way is up'. Nothing else is quite so helpful or important at a time when outside visual reference is lost. Supplied with a knowledge of the vertical, the pilot can confidently change height, speed and direction to conduct the flight according to plan.

The instrument displaying vertical reference is known as the Artificial Horizon and has pride of place at the top dead centre of the group. In its later development (Fig 6), it has other displays superimposed on it, but these have no effect on the basic horizon display in the background.

On this instrument there is a representation of the blue sky

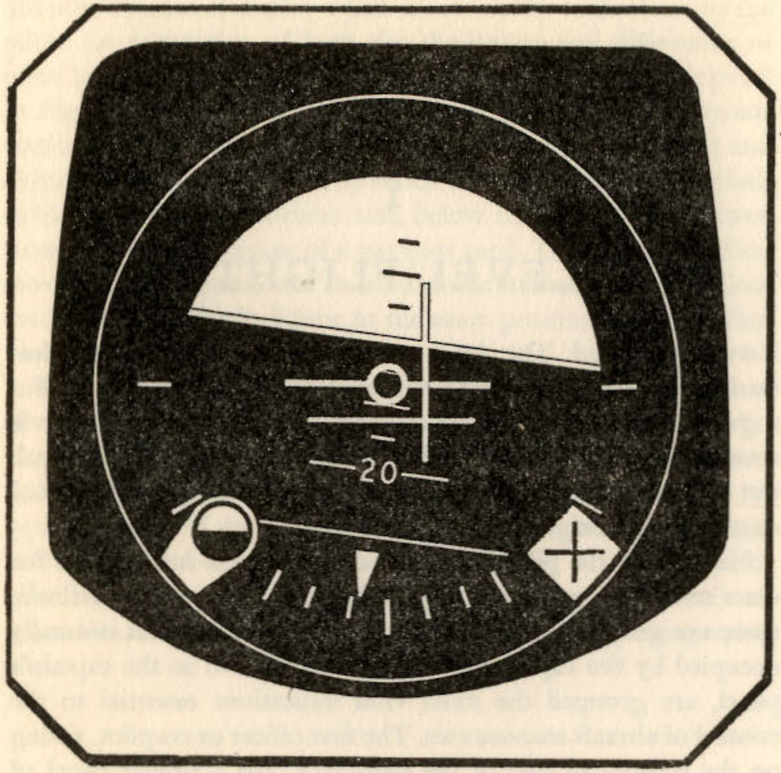


Figure 6 Director horizon. The horizon is represented by the division between the dark and light background and the aircraft by the winged symbol fixed in the centre of the dial glass

above and the dark earth below. The thin white line between the two is the horizon and this remains level with the real earth horizon during any manoeuvres performed by the aircraft. In the centre of the dial, a small winged symbol represents the aircraft as viewed from the rear. This tiny aircraft is firmly stuck to the glass and has no separate movement of its own.

With the instrument's horizon remaining in line with the natural horizon and the aircraft symbol fixed to the real aircraft, it follows

that the little aircraft in the picture shows exactly how the real aircraft is placed in relation to the unseen natural horizon. If the pilot rolls (some say 'banks') over to the left, the left wing will dip below the horizon line and this can be clearly seen in the display. As the little aircraft is stuck to the glass and cannot dip its wing to the left, it would seem that the artificial horizon has dipped over to the right to provide the required picture, but this is not strictly true. What has really happened is that the whole aircraft, its panel, the instrument case and the passengers in their seats have all rolled over to the left while the horizon line has remained level, as it always should.

It requires some effort, at first, to realise that the artificial horizon is not swinging about as the aircraft is rolled from side to side, but is, in fact, remaining level with the natural horizon while everything else is on the move. Everything else, that is, except the roll pointer—that little arrowhead in the bottom of the picture on British instruments and at the top on those of American design. This pointer is always fixed on a line at right angles to the horizon line and points straight up or down as the case may be. This little piece of knowledge can be very reassuring at times.

Read against the scale beneath it, the roll-pointer accurately shows the aircraft's roll angle from a wings level position. Without the help of actual numerals, it can readily be seen that the markings indicate 10, 20, 30, 60 and 90 degrees of roll angle. On instruments with the roll pointer at the top of the display, it is a little unfortunate that, when rolled to the left, the pointer is displaced to the right and vice versa but this is a small price to pay for the advantage of keeping the mechanism simple.

The pilot now decides to stop leaning over, or banking to the left and to level the wings. To do this, he moves the handwheel on top of the control column to the right and sees the little aircraft symbol in the dial rolling up level with the horizon. As it arrives there, he centralises the handwheel to stop the aircraft from rolling over to the right.

The artificial horizon performs another vital task in showing whether the aircraft has its nose up in the air or pointing to the

ground. A pull back on the control column to raise the aircraft nose will send the little aircraft in the display apparently rising into the blue sky above the horizon line. It is a sky conveniently marked with lines to show the angle at which the aircraft is pitched up from level. Similarly, if the control column is pushed forward to pitch down the aircraft nose, the little aeroplane will be seen below the horizon line in the dark area representing the ground.

This instrument, with its stable knowledge of how the aircraft is placed in roll or pitch, forms a basic reference against which the pilot can perform precise manoeuvres. It is a floor level indicator. In a climbing turn or a spiral dive it clearly displays pitch and roll angles or, in other words, aircraft attitude. For this reason it is sometimes called an Attitude Indicator or, when combined with a flight director, a Horizon Director Indicator (HDI).

As it would be unwise to place complete trust in such a vital indicator however well constructed and reliable it may be, an additional check is provided in the form of a brightly coloured warning flag which should spring into view within this dial if something has gone wrong with the instrument. This is to indicate that the information presented is probably not correct. Even if the flag is not in view, the safest attitude to adopt is to suspect that the artificial horizon is not telling the truth until convinced otherwise. The co-pilot usually has an identical horizon fed from an entirely separate source and, in a comprehensive system, the horizon displays are compared electrically. If there is a difference whose cause the system cannot locate, it will put up warning flags in both horizons just to be on the safe side. And, as yet another safeguard, the aviation authorities insist upon a third horizon as one of a group of standby instruments to which reference can be made when the two main instruments disagree. Of the three, two are likely to be in agreement and, on a majority vote, the third may then be rejected.

The standby horizon is of a simple design uncomplicated by additional display pointers and quite undemanding in its power supply requirements. On the day when all the generators on all

the engines fail to supply any power, the standby horizon can still be expected to function while there is life left in the aircraft battery. It is a good choice as an example to show the principle on which most horizons work.

The device which operates the horizon indication is, of course, a gyroscope. To be more explicit, it is a displacement gyroscope and it should also be mentioned that it is earth tied. The gyroscope (simply a spinning wheel), freely supported in pivoted frames called gimbals, will maintain the direction of its spin-axis in space. The faster it spins, the more firmly will it maintain its direction—a phenomenon generally referred to as gyro rigidity. If the case of the instrument is attached to the outermost gimbal supports and all the gimbals pivot freely, the case can be rolled and pitched without disturbing the gyro. By attaching a bar to represent the horizon as close as possible to the gyro, indication can be given of the extent to which the case, and hence the aircraft in which it is fitted, has been displaced.

More needs to be done, however, before it can be called an artificial horizon. A freely supported gyro can maintain any direction in space depending on where it happens to be pointing when power is applied to start it spinning. For this particular purpose, it is required to take up a position where its horizon bar is level with the real horizon. Not only that, but as the aircraft flies round the curvature of the earth, it must continually adjust to the local vertical. Otherwise the aircraft would tend to fly off at a tangent!

For these reasons, it is necessary to tie the gyro to earth's gravity by means of a gravity-sensitive system which will erect the gyro spin-axis to vertical and then keep it there. This can be achieved with the aid of mercury level switches operating small motors; both mounted on the gimbals.

A level switch consists of a slightly-curved glass tube with electrical contacts at each end and a drop of mercury in the centre. When the switch is not level, the mercury will run down to one end and bridge the contacts to complete a supply to a motor. The motor will move the gyro axis toward the vertical, where the

gimbals will level the switch thus removing the motor supply. When the gyro next wanders from vertical, the process will be repeated.

A curious feature of the gyroscope is its behaviour under any attempt to move its spin-axis. Instead of moving in the direction of the force applied, it strongly resists such movement and yet moves in a direction exactly at right angles to it. This property is known as precession and calls for a little cunning in positioning the erection motors so that they can achieve the desired result. It is no use expecting a motor to move the gyro axis directly. It would only move off in another direction at right angles to the one required. The answer is to fix the motor at another carefully chosen position on the gimbals and make it push in the very direction in which the gyro is not wanted to move. Fortunately, it will not move the gyro axis in that direction but it will cause it to precess in the direction required to bring it vertical. Engineers learn helpful rules to enable them to predict the direction of precession but it is, of course, the designer who most needs to know how it behaves. The motors, when operating, do not actually move but merely apply torque to the gimbal system to achieve the required result.

There are limits to what the gimbal system can do. Most of the simple horizons will continue to function properly even when the aircraft is rolled completely over any number of times. Large passenger aircraft rarely make use of this facility! In pitch, however, positions could be approached where the gimbals would line up in the same plane and virtually lock together. Mechanical stops are suitably placed to prevent this gimbal lock condition occurring. When a gimbal meets a stop, it feels that a torque is being applied to it. Precession then takes over and moves the gyro axis to some crazy angle far from vertical. The gyro is then said to be 'toppled'.

To sort out this situation, reliance has to be placed on the mercury switches and torque motors but first the aircraft must be in straight and level flight. Part of a pilot's expertise is to be able to reach this happy condition even with a toppled gyro by using

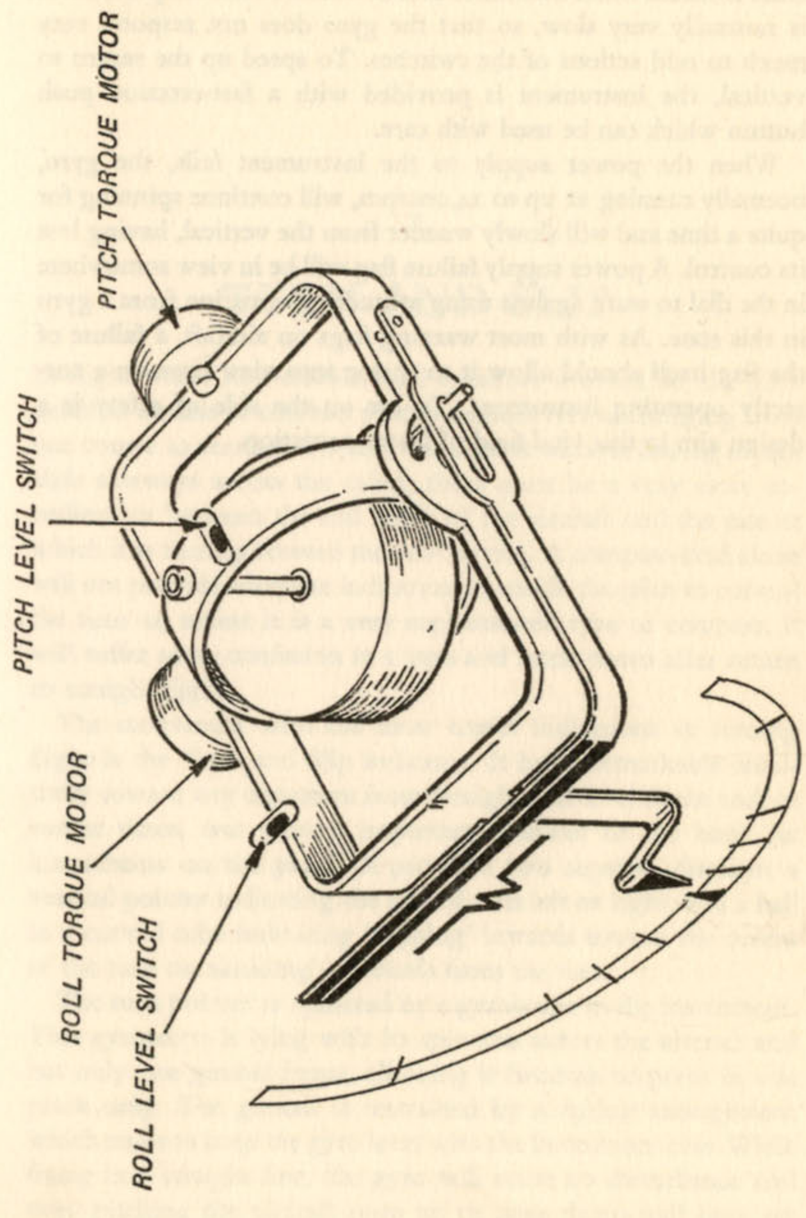


Figure 7 Artificial horizon gyro mechanism

clues from his other instruments. The action of the torque motors is normally very slow, so that the gyro does not respond very much to odd actions of the switches. To speed up the return to vertical, the instrument is provided with a fast-erection push button which can be used with care.

When the power supply to the instrument fails, the gyro, normally running at up to 24,000rpm, will continue spinning for quite a time and will slowly wander from the vertical, having lost its control. A power supply failure flag will be in view somewhere in the dial to warn against using attitude information from a gyro in this state. As with most warning flags on aircraft, a failure of the flag itself should allow it to spring into view even on a correctly operating instrument. To err on the side of safety is a design aim in this vital field of instrumentation.

2

TURN AND SLIP

In flight where no outside visual reference is available, the pilot needs to be able to conduct precise manoeuvres in changing from one course to another. To turn the aircraft without having things slide sideways across the cabin, there must be a very close co-ordination between the roll angle of the aircraft and the rate at which it is turning toward the new course. A compass-card alone will not provide adequate indication to enable the pilot to control the turn as, unless it is a very sophisticated type of compass, it will suffer some confusion in a turn and settle down after return to straight flight.

The instrument with the most useful indications in turning flight is the Turn and Slip indicator. It has a remarkable sensitivity toward any departure from straight and level flight and, in earlier times, was a most important member of the basic six instruments on the panel. It provides two separate displays: a vertical pointer indicating the rate of turn left or right, and a ball in a curved tube indicating 'slipping' inwards toward the centre of the turn or 'skidding' outwards from the turn.

The turn pointer is operated by a gyroscope in the instrument. This gyroscope is lying with its spin axis across the aircraft and has only one gimbal frame, allowing it freedom to pivot in one plane only. The gimbal is restrained by a spring arrangement which tends to keep the gyro level with the instrument case. While flying in a straight line, the gyro will sense no disturbance and even pitching the aircraft nose up or nose down will have no

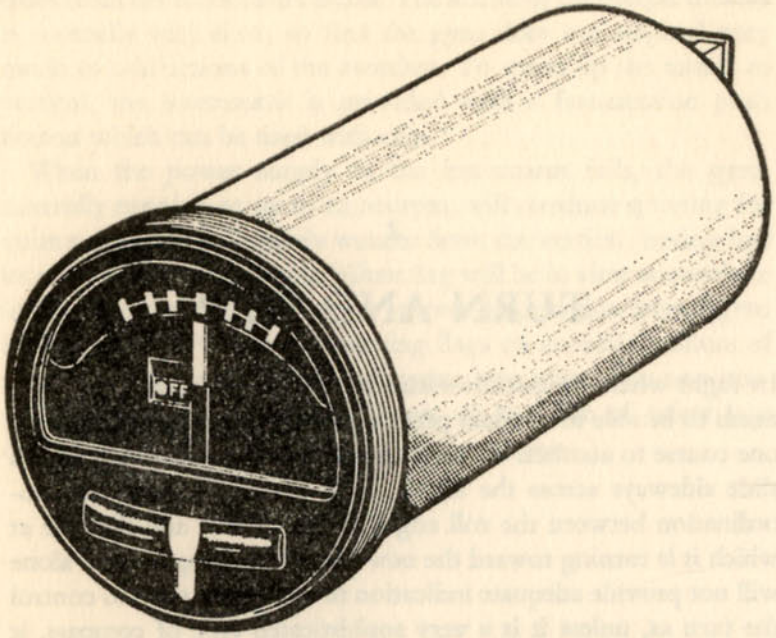


Figure 8 Turn and slip indicator

effect as such movements are simply rotating round the spin axis. If, however, the aircraft should turn about its vertical axis, such a movement would result in pushing the gyro spin axis out of its stable direction in space and cause gyro precession. Precession is movement of the gyro in a direction at right angles to the direction of the disturbing force and so must tilt the gimbal frame from its control position. The pointer, connected by gearing to the gimbal, will deflect to indicate that the aircraft is turning. The direction in which it moves shows the direction of the turn.

As the gyro precesses, the gimbal frame is restrained by the spring. The gimbal frame stops pointer deflection when the precession force is balanced by the tension in the spring. The tighter the turn, the greater will be the precession force and the more the pointer will be deflected. This property of the spring-restrained gyro gives it the ability to measure the rate at which the

aircraft is turning. In this role it is called a Rate Gyro. Unlike free gyros which tend to maintain a fixed direction in space regardless of aircraft manoeuvres, the rate gyro can be carried round by its spring and will give an output signal only while being rotated about its 'sensitive' axis. When the rotation ceases, the spring returns the gimbal frame and the turn pointer to a central zero position.

Even in straight flight, the turn and slip indicator is not ignored by the pilot. Concerned to maintain straight flight, he will find the turn pointer the most responsive warning of any tendency to wander from straight ahead. His flight may be properly conducted by maintaining level with the horizon, keeping the turn pointer central and checking the compass at intervals to see that no gradual change of direction has occurred during the various corrective control movements he has made.

The turn pointer moves over a calibrated scale to indicate the various rates at which the aircraft is being turned. The rates of turn are expressed in degrees per minute and are given a scale of numbers for the purpose of standardisation. A Rate 1 turn is 180° per minute, a Rate 2 turn is 360° per minute and so on. Early indicators had the scales marked with numbers for the various rates but later indicators have scale marks only and are intended only as a general guide to the turn rate. Some have marks to indicate Rate ½ which is a very gradual turn taking four minutes to complete one full circle. Some American indicators have the time, for example 4 MIN, painted on the dial, denoting the time it will take to complete a circle with the turn pointer held on the first mark away from centre.

Standard navigation procedures mostly call for Rate 1 turns in positioning an aircraft. The pilot, however, must not presume that following the turn indicator and using a stop-watch will result in steering the aircraft on to a correct course change. Only the compass can indicate the correct completion of a directional change.

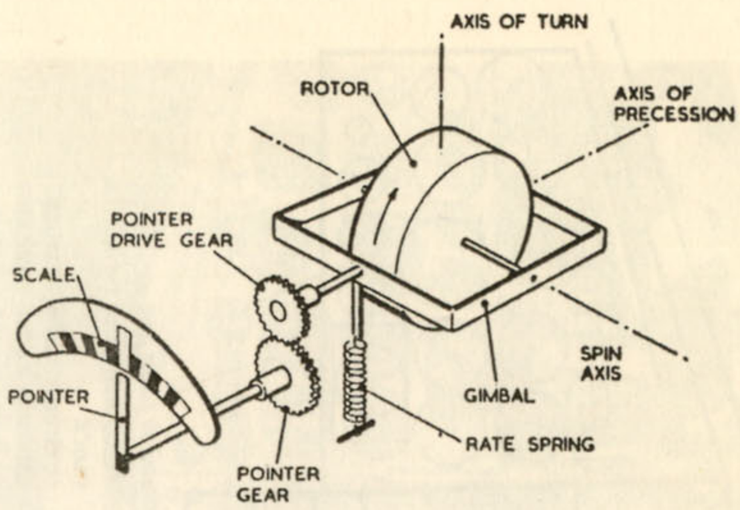
The second part of the instrument is the ball in a tube device known as the Slip Indicator. The tube is slightly curved and a

ball inside it normally rests in the lowest part of the tube at the centre mark. The ball is usually made of agate, a very hard form of silica and resistant to wear. The tube is filled with a clear fluid to slow down the movement of the ball and prevent it from oscillating wildly from side to side. The optical effect of the fluid in a round tube gives the ball the appearance of an egg standing on one end but this illusion presents no problem.

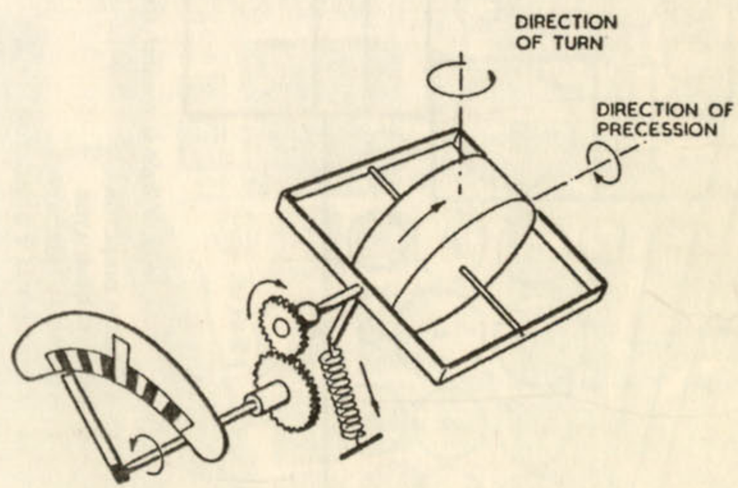
The action of the slip indicator is similar to that of a simple pendulum. The ball merely rolls to the part of the tube which is lowest according to the local gravity effect at any time. When the aircraft is turned, it must be rolled over in the direction of the turn so that the 'apparent' gravity remains vertical through the aircraft. If this is so, a passenger can walk down the aisle during a turn manoeuvre without crashing into the seating on either side. The pilot controls the aircraft so that the ball remains central during the turn. If he has rolled the aircraft too steeply for the rate of turn, the ball will move over in the direction of the turn and the aircraft can be said to be side-slipping. By a combination of rudder and aileron control, such a condition can be readily corrected and a properly co-ordinated turn achieved.

The ball slip indicator gave way to more complex mechanisms involving pendulous weights with vibration dampers and gearing, so that a sideslip pointer could be provided. After some years of experience with such instruments, however, the ball indication was re-introduced as being far more reliable than any other device.

As development of aircraft instruments and aircraft control has advanced, the turn and slip indicator has moved to positions of lesser priority in the panel layout. Originally one of the basic six indicators on the blind flying panel, it gradually moved out towards the edge of the panel and is now frequently found somewhere in the region of the captain's right knee. At the same time many later horizon indicators have a ball slip indicator mounted just below their displays. Some even have a turn pointer as an additional indication within the horizon display. In such systems, the rate of turn of the aircraft is ascertained by measuring the rate of rotation of the extremely accurate compass systems used.

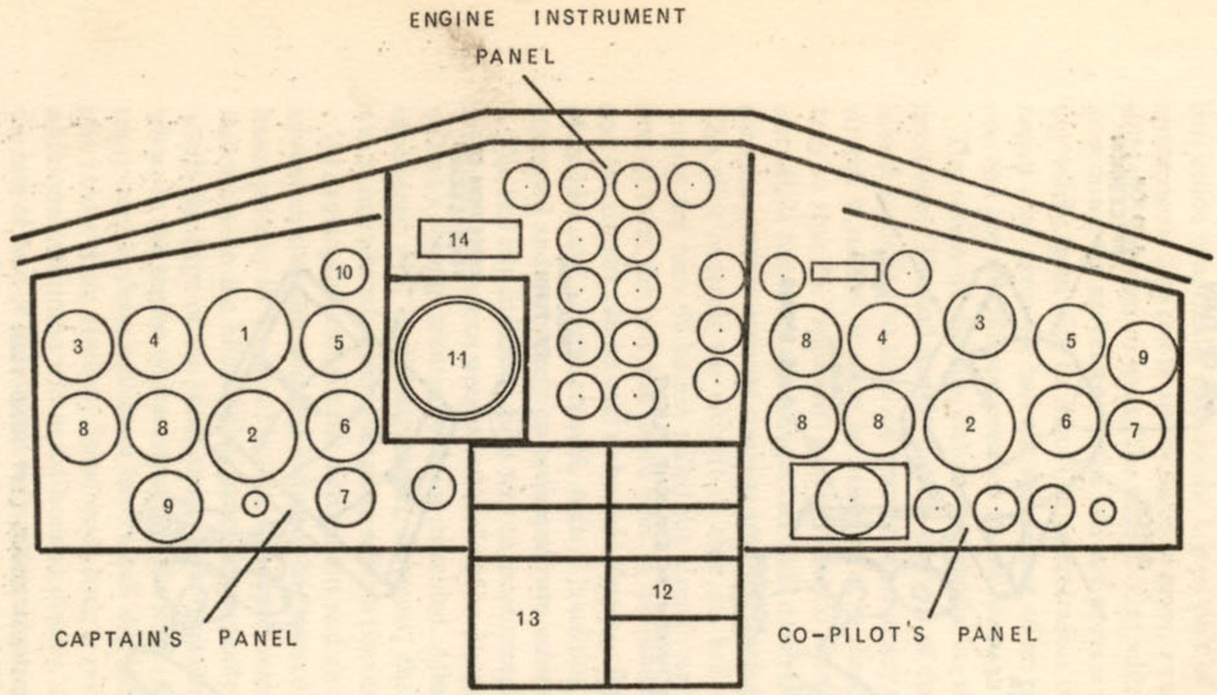


MECHANISM IN STRAIGHT FLIGHT



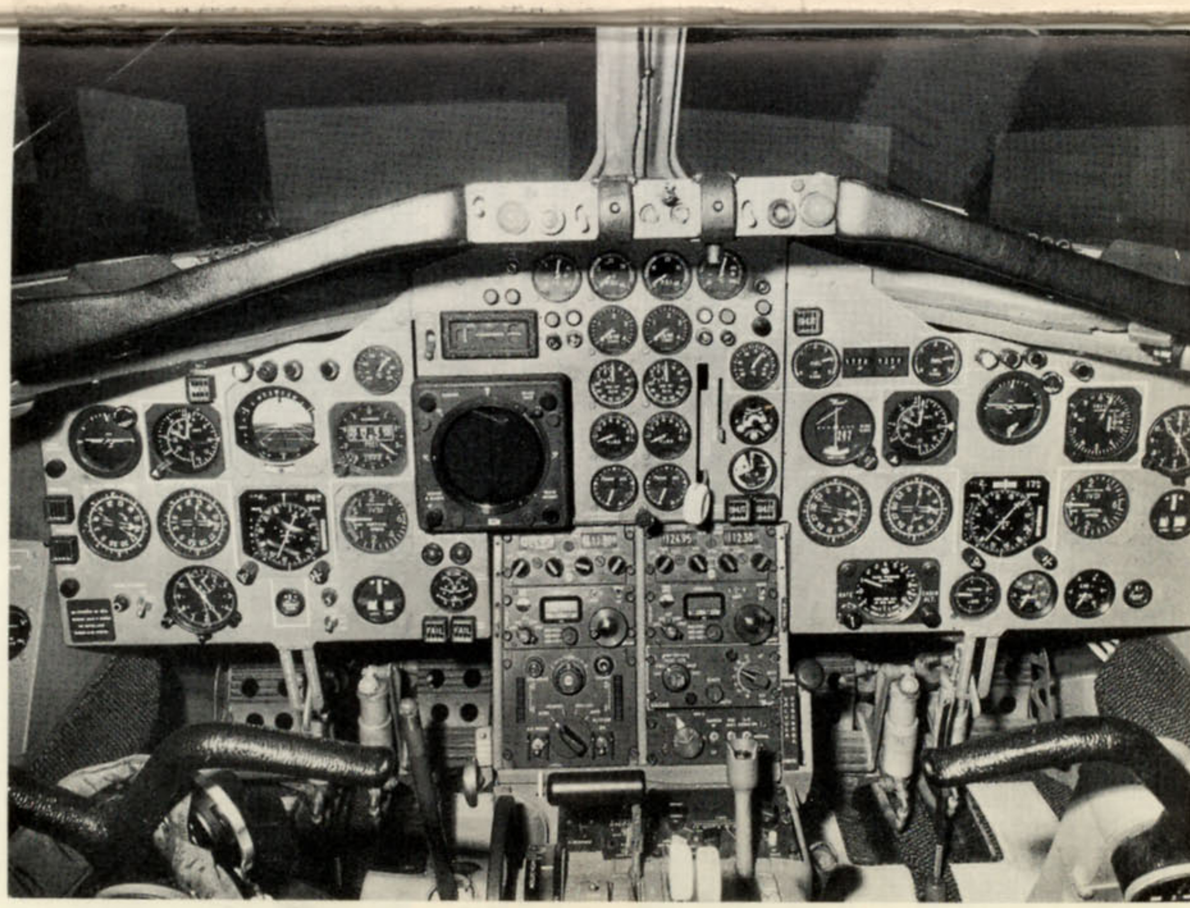
MECHANISM DURING LEFT HAND TURN

Figure 9 Turn and slip gyro mechanism

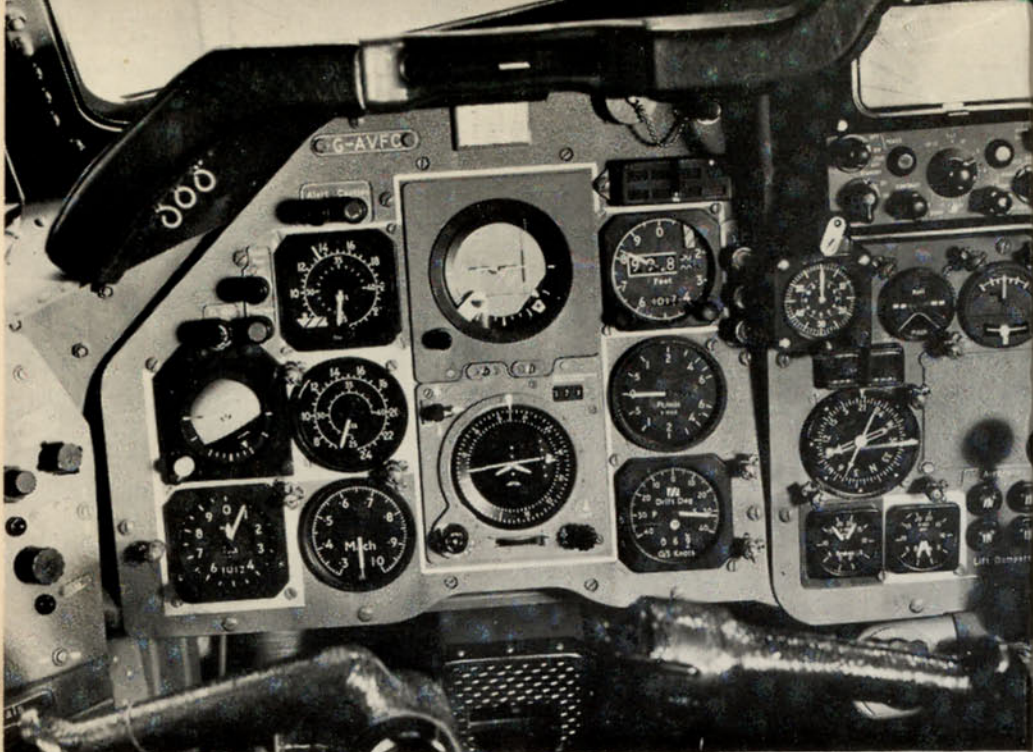


Key to flight instrument panel layout illustrated on facing page

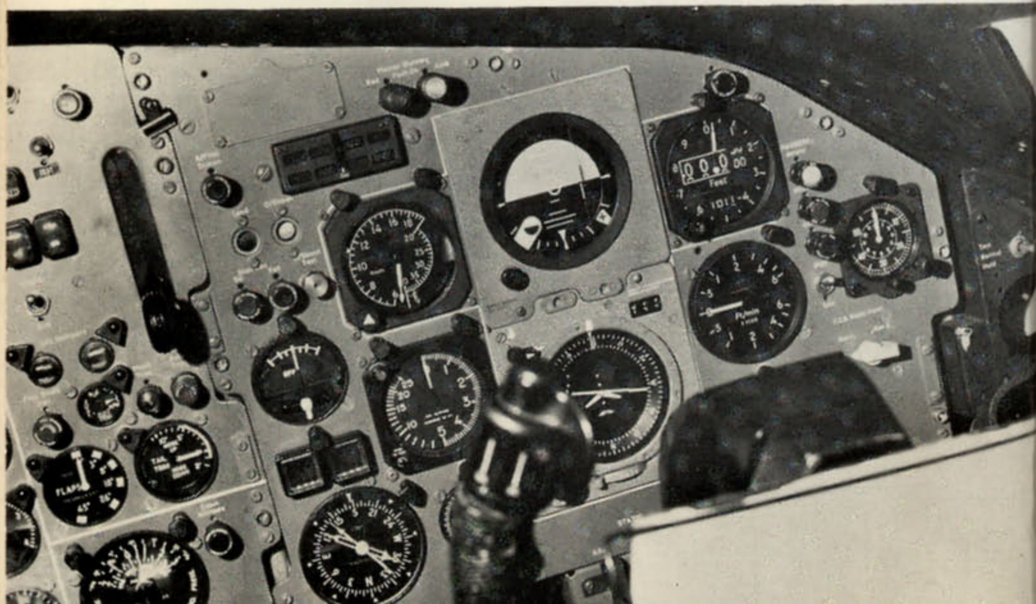
1	ATTITUDE DIRECTOR	8	RADIO-MAGNETIC INDICATOR
2	COMPASS INDICATOR	9	CLOCK
3	ARTIFICIAL HORIZON	10	OUTSIDE AIR TEMPERATURE
4	AIRSPEED/MACH INDICATOR	11	WEATHER RADAR INDICATOR
5	ALTIMETER	12	WEATHER RADAR CONTROL
6	VERTICAL SPEED INDICATOR	13	AUTOPILOT CONTROLLER
7	TURN & SLIP INDICATOR	14	AUTOPILOT TRIM INDICATOR



Page 35 Complete flight instrument panel layout of HS125 Executive aircraft. The captain's panel is on the left and the first officer's (co-pilot's) panel is on the right



Page 36 (*above*) Captain's panel of the Trident 2. Three standby instruments (horizon, airspeed indicator and altimeter) are grouped against the lighter background at the left. These provide a useful comparison with the main indications and maintain information flow when a main instrument fails; (*below*) co-pilot's panel of BEA Super One-Eleven. The main instruments on this panel are identical with those on the captain's panel and have electrical comparison circuits to give warning of differing indications



3

HOLDING COURSE

Knowledge of direction is an obvious essential to air travel. That most ancient of instruments, the magnetic compass, is still with us on modern aircraft and, now developed into a gyro-magnetic compass system, it displays its information directly below the horizon indicator in the centre of the panel.

The instrument includes a number of other indications and is generally called the Horizontal Situation Indicator (HSI). To understand its various displays, it is helpful to imagine the instrument removed from the panel and laid face upwards like the simple magnetic compass which preceeded it. Then all the pointers in the picture would literally point in the directions they are intended to convey.

The basic compass is represented among the elements of the display, not by a compass needle but, instead, by a rotating compass card marked 0–360°. At the top dead centre there is a lubber-line fixed to the case and representing the nose of the aircraft. The position of the lubber-line on the compass card is the direction in which the aircraft is pointing. Zero degrees represents north, ninety degrees represents east, and so on round the full circle. When the compass system is working, the card stands still over the landscape like the compass rose on ancient charts while the aeroplane, the instrument case and its lubber-line revolve around it. The aircraft's direction, read from the card against the lubber-line, is called heading and, while related to the earth's magnetic field, is called magnetic heading. The mariner steering north-west is, to the airman, on a heading of 315° magnetic.

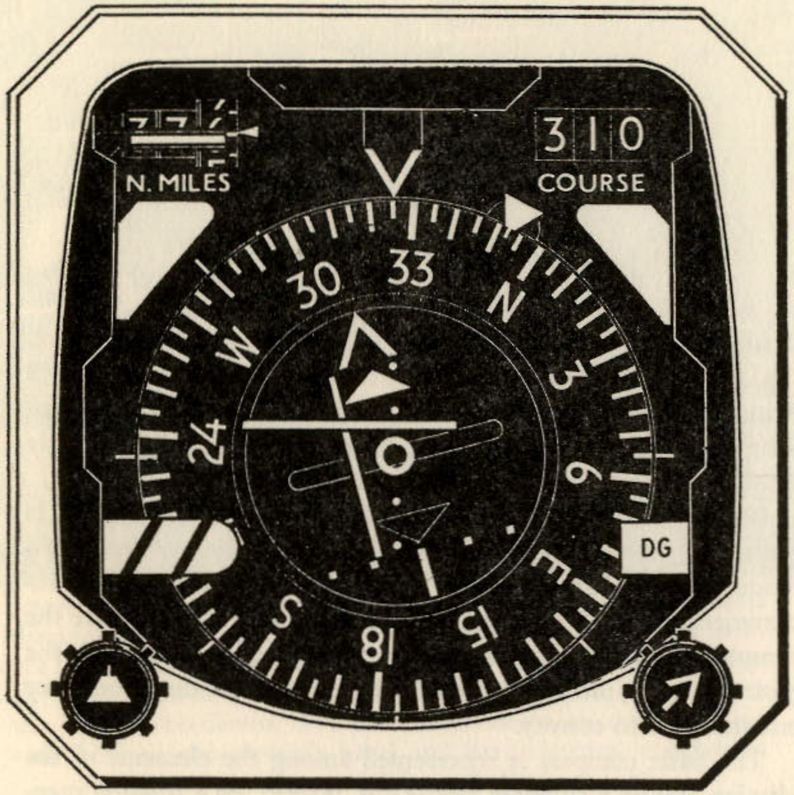


Figure 10 Horizontal situation indicator. This is the main compass indicator on the aircraft with radio guidance pointers in the centre of the display

A suitable compass system for aircraft use must meet a number of important requirements. It must not swing about with the aircraft's motion but remain steadily indicating the heading at all times. It must not be greatly affected by magnetism in the aircraft itself or by local irregularities in the earth's magnetic field. It must be powerful enough to drive its own compass card and, at the same time, drive repeater compass cards in other indicators and supply heading information to flight directors, autopilots and

anything else that requires it. The simple magnetic compass cannot possibly manage all this. It needs the assistance of a gyroscope.

A simple gyroscope suspended in a gimbal system will maintain its direction in space as mentioned in Chapter 1. If the axis of spin is arranged to be horizontal and a compass card attached to the gimbals, the device will serve as a very steady direction indicator. In this form, it is called a directional gyro (DG), or azimuth gyro (Fig 11). It does not know where north is or what direction in which it is pointing but it can be adjusted to display the correct reading by reference to a magnetic compass. Thereafter, unaffected by aircraft motion or local bends in the earth's magnetic field, it should give a stable indication of the direction in which the aircraft is heading. A synchro mounted on the gimbals can accurately transfer this heading reference to a remote compass card so that the gyro itself can be tucked away somewhere on the shelves of the equipment racking. Synchro outputs can be used to drive motors with enough power to operate elaborate indicators and as many additional compass cards as are needed.

The directional gyro, on its own, has one very important drawback for navigational purposes. While maintaining its direction in space, it is not maintaining direction on the turning earth below it. Its spin-axis is kept horizontal so that the gimbals are always correctly aligned but this is not the source of the problem. Consider such a gyro placed at the North Pole. An observer, sitting in a chair nearby, would be carried completely round the gyro in twenty-four hours while its spin-axis continued to point at the same distant region in space. The chilled observer would probably report that the gyro completed one full revolution during that period. This amounts to an apparent wander of 15 degrees/hour; not very good for a direction indicator but splendidly predictable. The observer and his gyro, now posted to the Equator, could cheerfully report no apparent wander at all. Banished next time to the South Pole, he would again observe an apparent wander of 15 degrees/hour but in the opposite direction from that at the North Pole. The effect varies with latitude according to a sine curve.

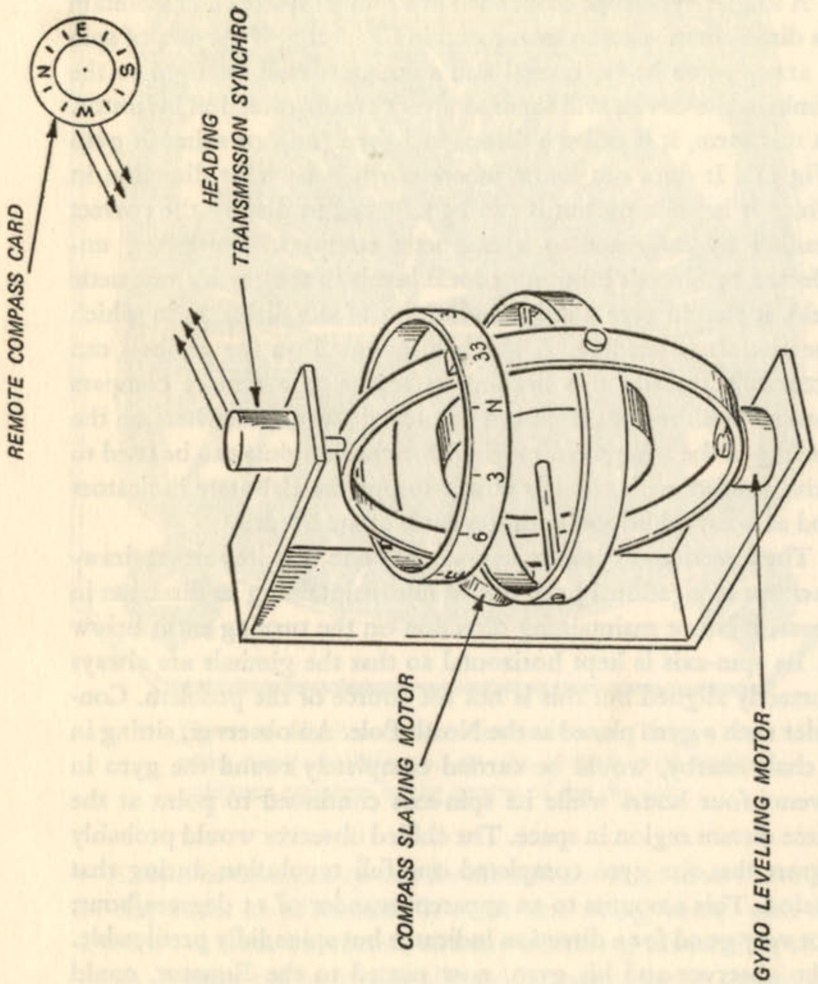


Figure 11 Directional gyro. The gyro maintains its direction in space and holds the compass scale steady for directional reference.

Faced with this problem, it is advisable to re-adjust the simple DG system every ten or fifteen minutes to make it agree with the magnetic compass. Automation has stepped in, however, and has provided a gyro-magnetic compass system in which the magnetic element makes the necessary corrections all the time. This gives the best of both worlds. As a system, it can be considered in two ways: a gyro slaved to magnetic north, or a magnetic sensing device stabilised by gyroscopic inertia. If the magnetic sensing goes unserviceable, the system is merely switched to DG and corrected to the other compass systems on board.

Control of the gyro to keep its spin-axis horizontal is usually achieved by a mercury level switch mounted on the gimbal system. The switch controls a torque motor similar to those in the vertical gyros of horizon instruments (Chapter 1). As the action of the torque motor will only precess the gyro, it must be placed on the gyro vertical-axis and try to rotate it in azimuth. This may seem a risky thing to do with a device which is supposed to be a direction indicator but the law of precession ensures that there will be no rotation in azimuth. Instead, the gyro will precess towards level where the mercury switch will centralise and remove the supply from the torque motor.

Having got the gyro level, the next thing to do is synchronise it with the output of a magnetic sensing device so that the compass card will indicate magnetic headings. This requires rotation in azimuth, and the way to achieve it is by using another torque motor which attempts to tip the gyro away from level. As long as the gyro wheel is spinning, precession never fails to do its party trick and results are achieved however devious the means.

Sensing the direction of the earth's magnetic field can be a delicate process in a large aircraft bristling with magnetic fields of its own. To obtain such information in a form which can be used to precess a gyro calls for something a little more sophisticated than a magnetised needle. In fact, the device uses no magnet at all! It is usually known as a compass Detector Unit but sometimes as Flux Valve or Flux Gate, giving a clue to its operation. It consists of a group of electrical coils suspended on a short pendulum

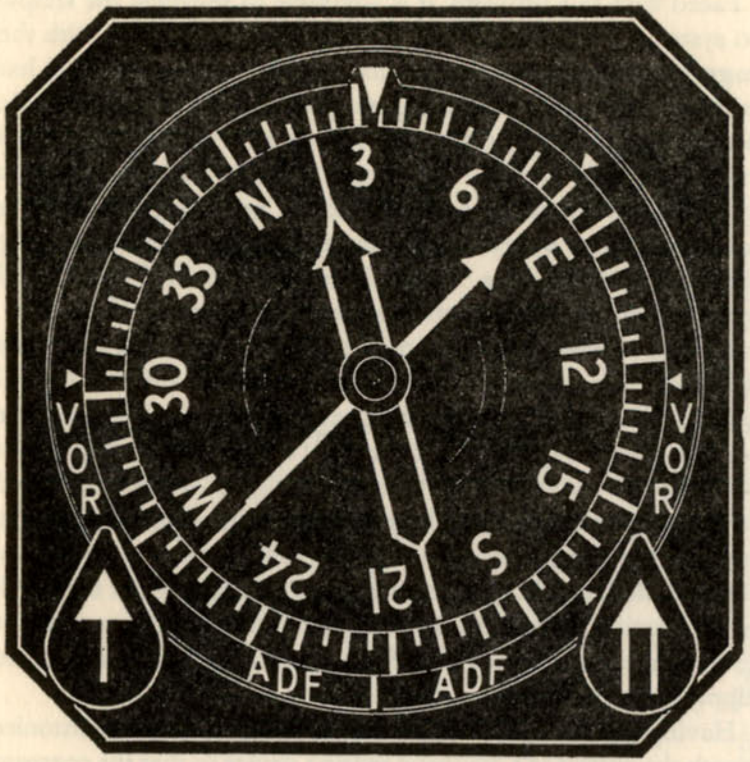


Figure 12 Radio magnetic indicator. The compass card on this indicator is a repeater of the main compass card and the pointers indicate the direction of selected ground radio beacons

by means of a pivoted joint which allows it to swing in any direction but not to rotate. In this way, the coil pattern can lie horizontally in the earth's magnetic field most of the time. An alternating electric current fed to the coils intermittently excludes earth's magnetism and allows it to return. Effectively, earth's magnetic field is fluctuating across the coil pattern and will induce tiny currents in the coils in proportions which depend on the direction in which they are pointing. Those tiny currents are applied to a precession amplifier which produces the appropriate

drive output for the gyro torque motor. When the compass card, driven round by the gyro, reaches a position which agrees with the detector unit, no further error signal is produced and precession ceases until a further difference occurs between these two.

Compass detector units are usually mounted in the aircraft wing-tips where they are as far as possible from most of the disturbing magnetic fields within the aircraft. Even so, it is necessary to compensate for disturbing influences either by feeding carefully adjusted correction currents to extra coils in the detector units or by the addition of tiny adjustable magnets. The compass swing is a procedure in which the grounded aircraft is placed on many magnetic headings in turn so that the appropriate adjustments can be made to reduce all errors to less than one degree. It involves one man at a distance from the aircraft taking sights on it with an accurate compass on a tripod and reporting each time what the aircraft compass system should read. The great steel tractor towing the aircraft round in circles can cause problems of magnetism if it moves too near to a detector unit, but an accurate compass swing is an airworthiness requirement however difficult it may be to perform. The remaining errors on the various headings are recorded on a deviation card which is placed in view of the pilot.

The centre of the compass card is cut out to display radio deviation pointers. Together with the aircraft symbol pointing straight up the dial, these define the relationship of the aircraft to radio beams from ground transmitters. An instrument including these features is normally called a Horizontal Situation Indicator (HSI). The pilot must be concerned not only with where the aircraft is pointing but where it is positioned in relation to radio tracks known as airways.

The airways are set out as particular directions to or from Very-High-Frequency Omni-Range, VOR radio beacons. Such a beacon is shown in Fig 13. It transmits in all directions and the aircraft receiver can be selected to track along any particular direction towards or away from the beacon. Although the number of directions which could be selected is infinite, in prac-

tice only whole numbers of degrees are selected as if there were 360 spokes to the wheel. These are known as radials. The beacons are all aligned with magnetic North so that any selected radial corresponds to a compass heading in degrees. In following airways, the aircraft is travelling from beacon to beacon on specified radials. The airways are chosen to be ten miles wide and aircraft on them must not stray outside the five-mile limit on either side of

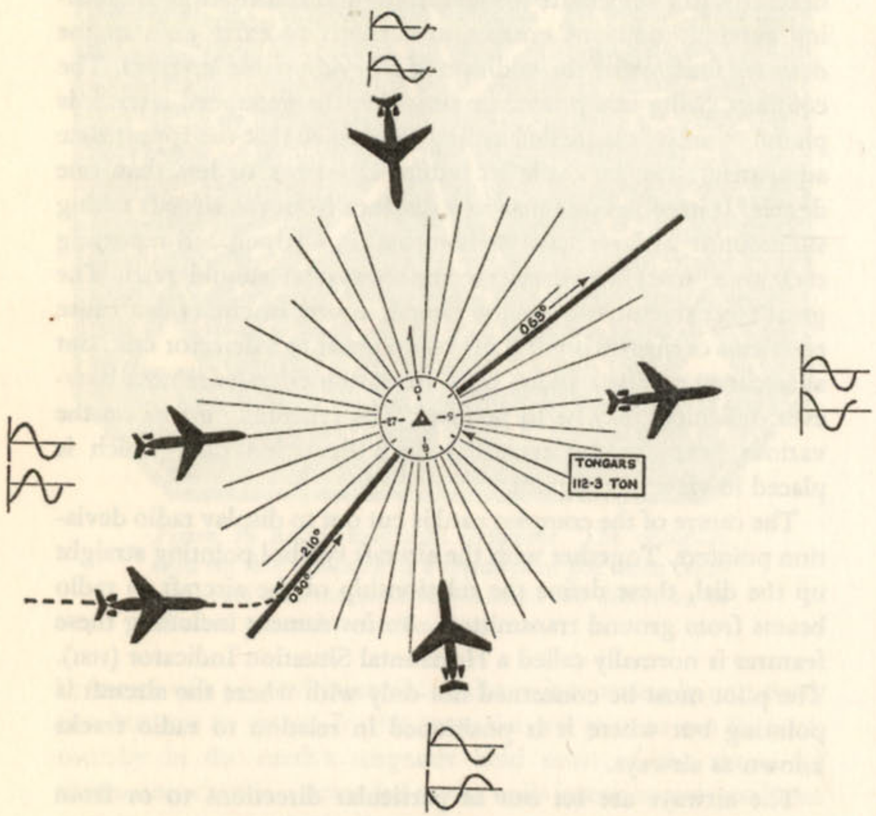


Figure 13 VHF Omni-Range beacon (VOR). Aircraft flight control systems can be selected to fly along radial courses towards or away from the radio beacon. Thus aircraft fly from beacon to beacon on radio-defined airways

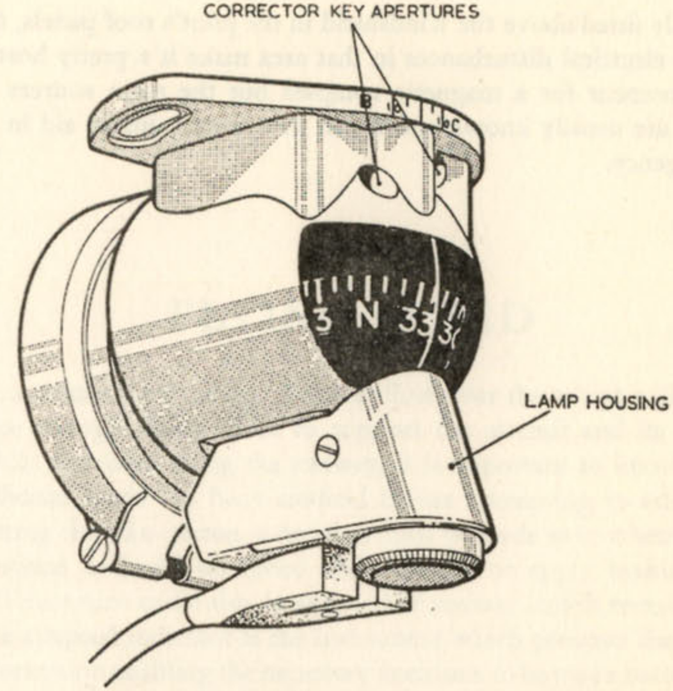


Figure 14 Standby magnetic compass. This simple magnetic compass is used when gyro electrical failure affects the aircraft's main compass systems

centreline. The radio-deviation bar in the centre of the HSI display is central under the aircraft symbol when the aircraft is centred on the selected radial. If the radial is out to left of the aircraft, the deviation bar will also be out to the left of the aircraft symbol. The pilot can simply steer the aircraft to the left to bring it back on to the radial.

The gyro-compass systems on the aircraft need main power supplies to drive and operate them. In case those power supplies fail, it is necessary to have a simple magnetic compass as a standby. The Smiths standby compass in Fig 14 is a typical example. It is fitted with tiny adjustable corrector magnets to compensate for aircraft magnetic fields and is capable of reasonable accuracy.

Usually fitted above the windshield in the pilot's roof panels, the many electrical disturbances in that area make it a pretty hostile environment for a magnetic compass but the main sources of error are usually known and it can be a very valuable aid in an emergency.

4

FLYING SPEED

AT a certain forward speed, the airflow over the wings will produce enough lifting force to support the aircraft and its load. While travelling along the runway, it is important to know that sufficient speed has been attained before attempting to take-off. During the take-off run, a decision must be made as to whether to continue to build up speed and take-off, or apply braking in sufficient time to be able to stop in the runway length remaining. The airspeed indicator is the instrument which presents the vital information enabling the necessary decisions to be made both then and throughout the flight. It is positioned to the left of the horizon indicator in the standard panel layout.

The scale of the airspeed indicator is marked in knots (nautical miles per hour) and indicates merely the speed of the aircraft through the air. If the great air mass in which the aircraft is flying is moving at speed, the airspeed indicator doesn't know about it, nor does it care. It is the speed of the aircraft through the air which determines the amount of lift produced; not its speed over the ground.

Examining the scale of the airspeed indicator shown in Fig 15, it will be seen that it has a long pointer indicating knots, with graduations at intervals of two knots, while a short pointer indicates hundreds of knots. The pointers will never return to zero but will rest at 40 knots. Speeds slower than this would be difficult to measure accurately with a delicate instrument covering such a large range.

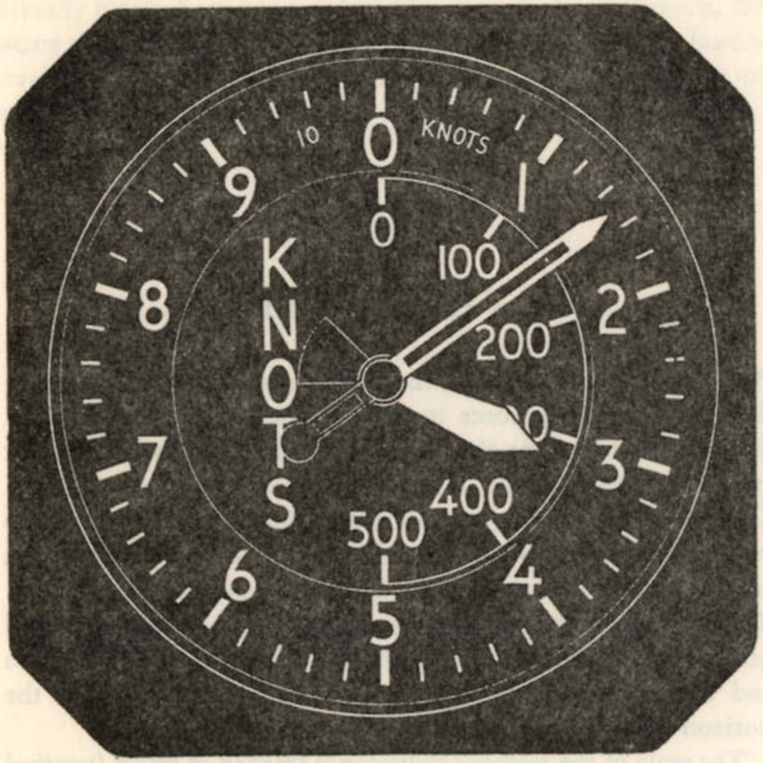


Figure 15 Airspeed indicator

Now to take a look inside the airspeed indicator, generally known as the ASI. It is best described as a differential pressure gauge and a glance at Fig 16 will show what this means. The case of the instrument is sealed air-tight and the only connections with outside air pressure are through two tubes at the rear. One leads into a thin expanding metal box, called a capsule, to which the pointer mechanism is attached. The other tube leads to the inside of the instrument case where its air pressure can act on the outside of the capsule. These tubes are connected by hoses to a system of piping in the aircraft known as the pitot/static system. This system carries two air pressures to a number of indicators and

other devices and its function is best understood by considering how it operates the airspeed indicator.

Pitot pressure, named after Henri Pitot (1695–1771), is supplied by an open-ended tube pointing forwards into the airflow. It is usually found near the nose of the aircraft. The pressure built up in this piping is the outside air pressure plus the increase of pressure due to the forward speed of the aircraft.

Static pressure is the outside air pressure around the aircraft and this is supplied by an open-ended tube called a static vent and mounted flush with the side of the aircraft. Hopefully, this vent will register outside air pressure regardless of aircraft speed. All the pipelines are duplicated as a precaution against leaks or blockage and a third system is also provided to operate standby instruments in case of failure.

Pitot and static pressures are applied to the capsule in the airspeed indicator; pitot inside the capsule and static outside. Pitot pressure partly consists of static pressure, so static pressure is inside the capsule also. The result of this arrangement is that static pressure, acting equally both inside and outside the capsule, has no effect on the capsule. The only effective pressure remaining to expand the capsule is the pressure built up due to the aircraft's forward speed and this is what has to be measured. As a quantity, this dynamic pressure (pressure due to movement) is referred to by the letter 'Q' and is a measurement of the air-loading, due to forward speed, on the front surface of the aircraft. By attaching a pointer mechanism to the capsule and marking the pressure scale in knots, an indication of airspeed is provided. It can thus be seen that the differential pressure capsule is a simple computer always performing the subtraction:

Pitot pressure – static pressure = dynamic pressure

The transport aircraft, in common with the bicycle, needs speed not only to travel from place to place but also to maintain stability and control. On the take-off run, the build-up of speed is of importance second only to that of keeping off the grass! As mentioned earlier, the first requirement is to achieve decision speed V_1

at a point which still leaves enough runway ahead in which to stop the aircraft. Having made the decision to go on, the next speed needed is rotation speed V_r. If the control column is then pulled back to rotate the aircraft into a nose-up attitude, thereby increasing the lift on the wings, it can be expected to lift off the ground. Speed should still be increasing, and before flying over the end of the runway flight safety speed V_2 should have been reached and this at a height of not less than 35ft above the runway surface to meet the aircraft performance requirements. In practice, of course, this minimum is normally exceeded by a comfortable margin.

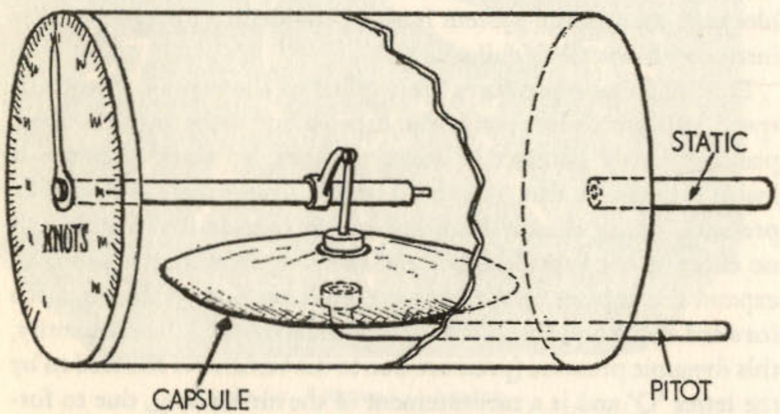


Figure 16 Principle of the airspeed indicator. The capsule expands by pressure increase due to the aircraft's forward motion through the air

With maximum climb power set on the engines the nose can then be raised still further to climb at a suitable rate. While doing this, it is essential to see that the airspeed is maintained despite the high nose-up attitude, since raising the nose results in a loss of airspeed. The real concern is to avoid too high an angle-of-attack which would lead to the undesirable manoeuvre known as a stall.

Angle-of-attack is the angle formed between the wing and the direction of the airflow which meets it. It is also called incidence

(though this term more precisely used refers to the fixed angle between wings and fuselage). Too large an angle-of-attack causes the airflow over the top of the wing to break away into a turbulent flow, resulting in loss of lift and a somewhat undignified descent. The only cure for the stall is to lower the nose, which tends to happen anyway on most aircraft in a stall, and gain airspeed to reduce the angle-of-attack. Near the ground, loss of height in recovering from a stall can seldom be afforded so a frequent check must be made on the climb to see that airspeed is not reducing, ie, the angle-of-attack is not increasing.

Now safely established on the climb, some of the properties of the atmosphere and their effect on the measurement of airspeed, are to be considered. As is generally known, atmospheric pressure becomes less with increase of height. Initially, the temperature also decreases. These two conditions alter the density of the air in a way which results in a decrease of density with increase of height, and this has a very significant effect on the operation of the airspeed indicator capsule. In the less dense air of the upper atmosphere, the pitot tube must be carried very much faster forward to build up the same dynamic pressure found at quite moderate speed at sea level. In other words, when flying high, the airspeed indicator grossly under-reads. At 40,000ft, it is indicating about one-half of the aircraft's actual airspeed!

At first sight, it would appear that a simple differential pressure gauge is of little use as a speed indicator, but this is not so. Remembering that it is an indicator of 'Q', the dynamic pressure load on the front of the aircraft, it will be realised that the same spot on the dial means the same 'Q' at any height; means the same angle-of-attack or the same margin away from the stall. Thus the stalling angle-of-attack can be quoted in terms of knots and will hold good at all heights. Similarly, limitations in the amount of 'Q'—such as the maximum at which the wheels may safely be lowered, or the maximum permissable 'Q' imposed on the aircraft structure—can also be precisely quoted.

All such limitations can be quoted in knots IAS (indicated airspeed), without specifying any height and this makes flying less

complicated. All that it is necessary to remember is that IAS does not tell how fast the aircraft is travelling but is nevertheless useful in a number of other ways. The information it affords is embodied in such terms as stalling speed V_s, normal operating speed V_{no}, and the never exceed speed V_{ne} and many others, all of which are higher actual speeds at greater heights in the atmosphere.

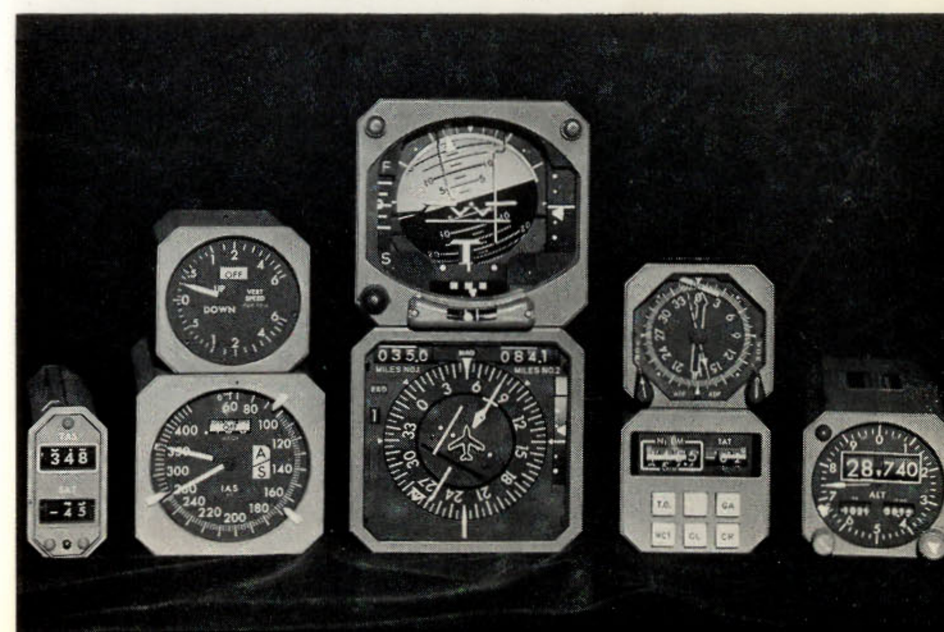
To obtain true airspeed (TAS) from the indicated airspeed (IAS), a simple calculator is needed. This is a plastic disc with movable scales usually carried in the pilot's navigation bag. On it can be set the height at which the aircraft is flying and the temperature at that height, obtained from the altimeter and the outside air temperature indicator respectively. The true airspeed can then be read off the face of the plastic disc. Some aircraft carry a true airspeed indicator on the panel in addition to the simple ASI. Such an instrument requires a sealed capsule and a temperature probe to modify the action of the differential capsule.

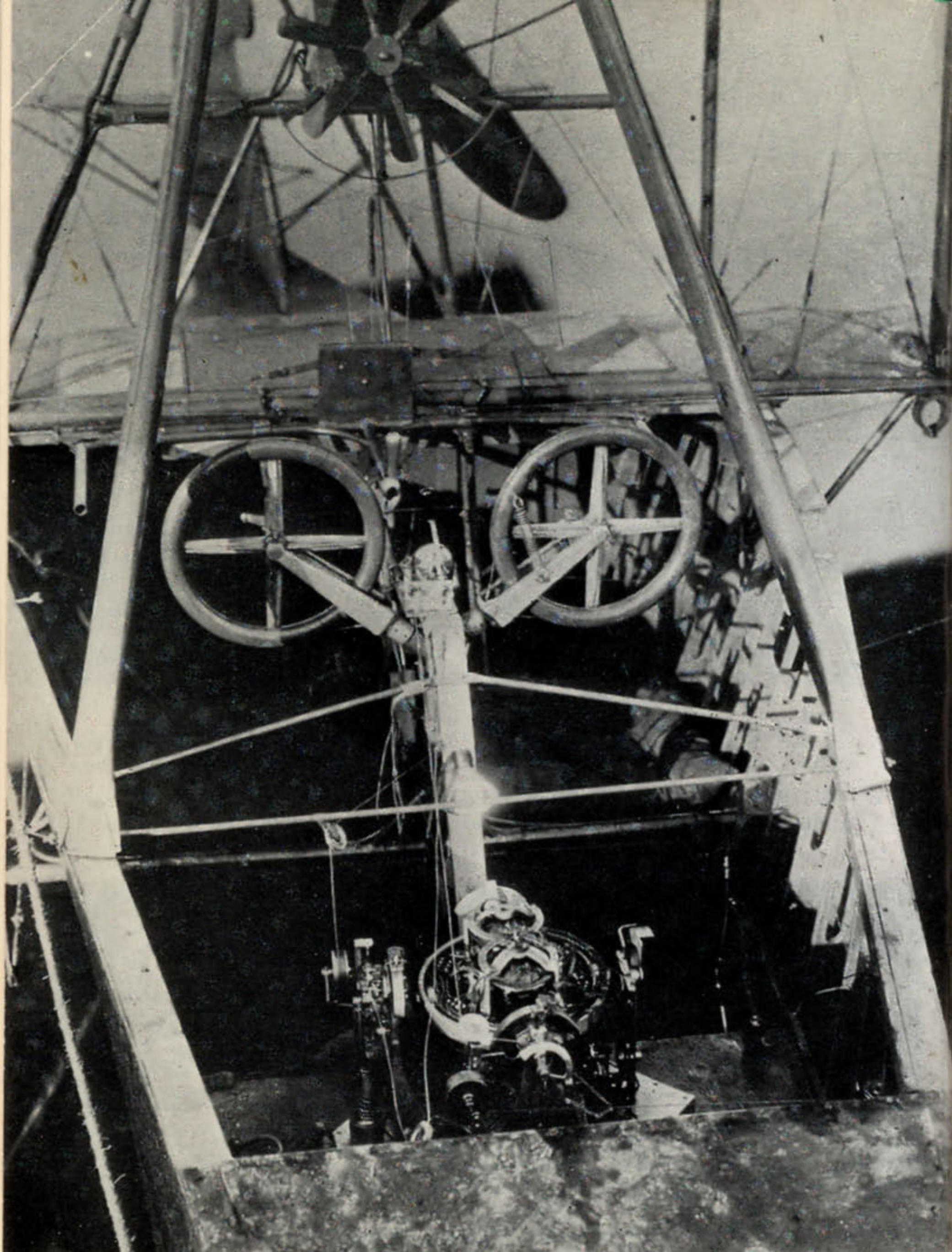
The greatest feature of modern air transport is its speed and it is very tempting to assume that one can run the engines up to full power and let them drive the aircraft onward as fast as the 'Q' force will allow. There are, however, strict limitations to be observed. An aircraft structure is designed for a particular strength. Too much force applied to that structure would eat into the safety margin and eventually cause structural failure. Also, the airflow over the wings, following a curved path, is speeded up and will approach the speed of sound as the aircraft's speed is increased. At near-sonic speeds, the air will form a pattern of pressure waves known as shock waves over the wings, and these can be disturbing to the control surfaces of an aircraft not designed for supersonic flight. For these reasons, it is necessary to limit the indicated airspeed to a reasonable maximum usually referred to as the normal operating speed V_{no}.

On entering a region of air turbulence, where sudden heavy air loads may be encountered, it is necessary to reduce speed slightly to lessen the effect of such loads on the structure. This lower limit is known as the rough air speed V_{ra}.

The testing of capsule-operated indicators in the instrument

Page 53 (*above*) A flight director system of the future. The Sperry EADI system replaces the mechanical horizon by a cathode ray tube on which realistic and symbolic displays are presented to the pilots. Here the aircraft is approaching a runway a little too high and left of centre line; (*below*) Sperry flight system instruments selected for the DC-10 wide-body jet





Page 54 Lawrence Sperry's award winning autopilot fitted in a Curtiss seaplane about 1912. This is a view looking rearward over the cockpit. The autopilot gyroscope unit can be seen lower centre and the joystick with its two large handwheels beyond

workshops can be a long process requiring a sustained level of concentration. In following the basic method of testing, most indicators of this type are placed in a sealed pressure chamber with a glass door through which the dials can be seen. Usually, a vibrator is attached to the instrument support frame to make all the gears and shafts dance up and down in their pivots and prevent the pointers sticking in various positions. This is not really cheating because the instruments receive at least some vibration during their normal working life even on the smoothest of modern jets.

Air pressure, or vacuum, can be applied to the chamber and to the instruments to simulate various conditions of altitude and speed. These pressures are very accurately measured using a mercury manometer not unlike some of the tall and delicate barometers of the past. Great care, and perhaps some luck, are needed to keep the mercury in the tube when operating the pressure control valves. Mercury scattered on the bench and floor is an expensive waste of mercury, while mercury in the chamber or, worse still, in the instruments, is an expensive waste of instruments!

Most capsule-operated instruments have sealed cases to prevent aircraft cabin pressure entering and ruining their operation. A preliminary check is necessary to ensure that the case sealing is intact before proceeding with a long series of tests at various pressures. It is convenient to lead a tube from the instrument out to a jam-jar of water on the bench and then set up a suitable high pressure in the chamber. If no bubbles appear in the water, it may safely be assumed that the case is not leaking. The remainder of the checks can then be carried out at simulated altitudes of 10,000ft, 20,000ft and so on with some hope that, hours later, some instruments can be certified as serviceable and within the required limits of accuracy.

5

MEASURING ALTITUDE

WITH wings level, on course, and with adequate speed to maintain the climb, there is now time to take a look at the altimeter to see what height has been gained.

In the modern digital altimeter, the height is set out very clearly in large figures in the upper half of the dial. The reading is in feet, and the instrument is, in fact, simply a barometer measuring air pressure. The only difference is that, instead of 'Stormy', 'Change' and 'Fair' being printed round the dial, it has a scale with figures reading hundreds of feet. Air pressure at any particular place changes from day to day so, if the altimeter is to be an accurate indicator of height, compensation for these changes must be made by adjusting the knob on the instrument. In this way, the correct pressure of the day can be set on the row of small figures, reading millibars, in the lower half of the dial. Near the ground, one millibar change represents about 30ft in height. The Control Tower will advise what the pressure setting should be, but first it must be decided from what level it is appropriate to measure the height.

If the aircraft was flying low down in the vicinity of the airfield, the captain might well be interested in his height above the runway. In this case he would simply ask the controller for 'QFE' (using the Q-code to keep the radio chat brief). The controller would reply with the pressure at the time, quoted in millibars, and when this was set on the millibar scale the aircraft's altimeter would indicate its height above the runway.

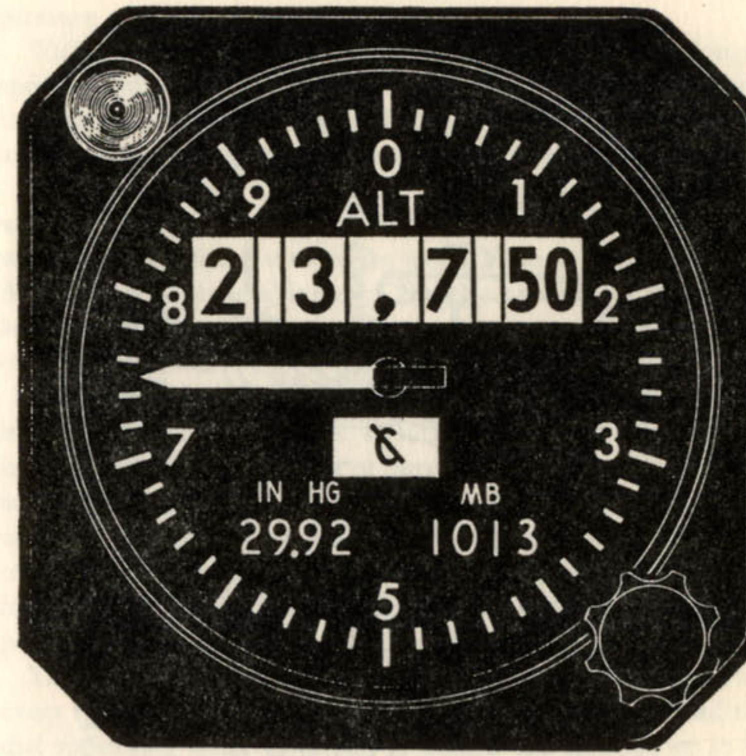


Figure 17 Digital altimeter

If, however, the captain was more concerned with his height above sea level, he would ask the controller for 'QNH'. The pressure he would then quote would enable him to set his altimeter to indicate height above mean sea level, known as altitude.

But now, climbing towards cruising level and leaving miles of airspace below, the important thing is to arrive at the correct altitude as directed by Air Traffic Control and thereby maintain adequate height separation from other traffic in the vicinity. This is easily done by arranging that all aircraft above what is called Transition Altitude, usually 3,000ft, shall adjust their altimeters to

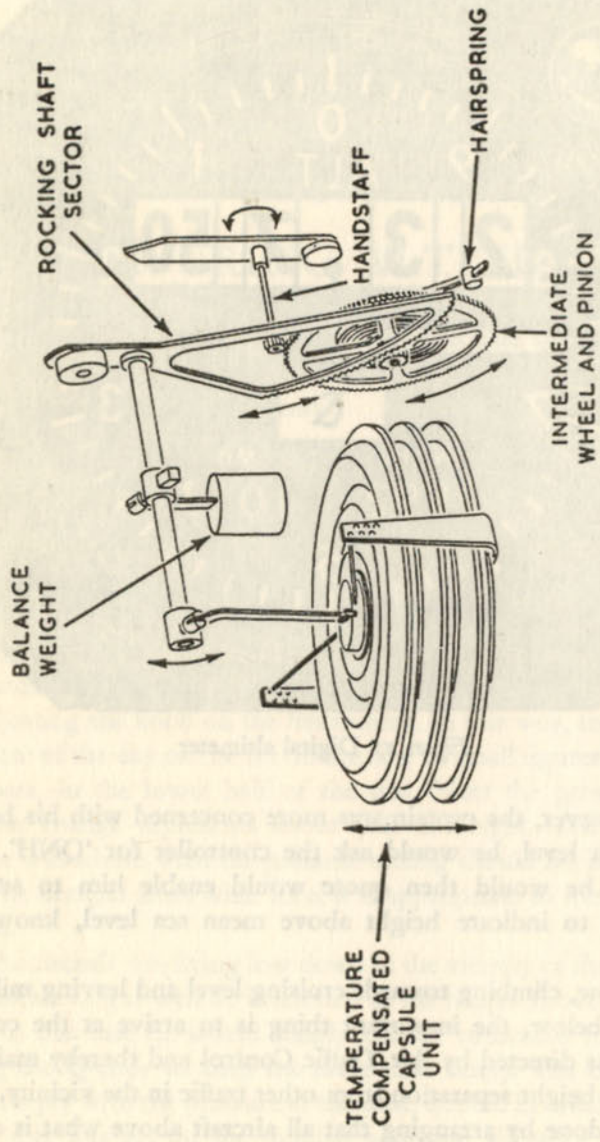


Figure 18 Altimeter capsule mechanism

the standard setting of 1,013·25 millibars. This is sea level pressure on a normal day.

With standard setting on the altimeter, the pilot will no longer speak of altitude in feet but will refer to Flight Levels, which are the number of hundreds of feet. Thus 10,000ft is Flight Level 100, and FL 240 means that the altimeter will read 24,000ft.

Pressure decreases with increase of altitude in a fairly uniform way. Sub-sonic jets can operate most efficiently at around 40,000ft while Concorde flying at twice the speed of sound prefers 60,000ft. Air pressure at these altitudes is roughly one-fifth of that at sea level, so the altimeter has quite a range to cover in coping with today's aircraft.

The mechanism of the altimeter is operated by a capsule which is a sealed circular metal box with corrugated ends which allow it to expand with a reduction of outside air pressure. The capsule is evacuated of most of the air inside it before it is sealed and this near vacuum gives it the name of Absolute Capsule. Usually a number of these capsules are joined end to end so that their individual movements add up to do the work of pushing the pointers round the dial, as shown in Fig 18.

The large pointer of an altimeter completes one revolution for every thousand feet, so that the capsule must move it round the dial something like forty times in getting the modern jet to its operating altitude.

The digital altimeter in use today, indicating altitude in a row of figures in addition to a pointer, usually has an electric motor to enable the delicate capsule to deal with the extra work involved. On the larger airliners, its capsule is found in a large black box, called an Air Data Computer, and tucked away on the shelves. The indicator then merely repeats the altitude sensed by the remote computer.

To understand how the altimeter came to be adopted in its present form, it is necessary to look back a few years to the time before the digital altimeter made its debut. At that time, the Sensitive Altimeter, as it was called, had a circular scale and three moving pointers, a long one indicating hundreds of feet, a short

Figure 19 Multi-pointer altimeter

broad one indicating thousands of feet, and a tiny one in the background indicating tens of thousands. An example of such an instrument in use for many years is shown in Figs 19 and 20, and it will be evident that a certain amount of skill was required in reading it, especially at times when only a passing glance could be spared. Look at one of its positions shown in Fig 20. Is it reading eleven thousand feet or is it reading a mere one thousand? Ten

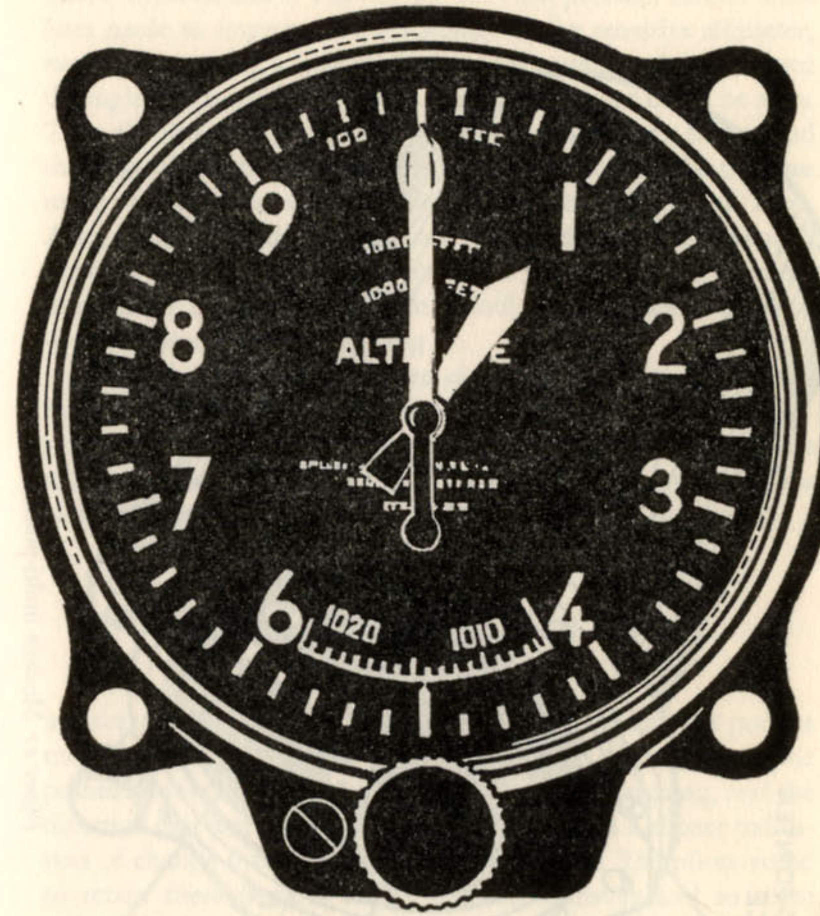


Figure 20 Multi-pointer altimeter with 10,000ft pointer obscured

thousand feet difference and yet a very similar picture. The possibilities of misreading this instrument are all too real. Clearly, something has to be done!

The short-term answer was a flashing green 10,000ft warning light on the panel. This is still with us. Labelled FL 100 Warning, it starts to flash every time the aircraft in which it is fitted descends

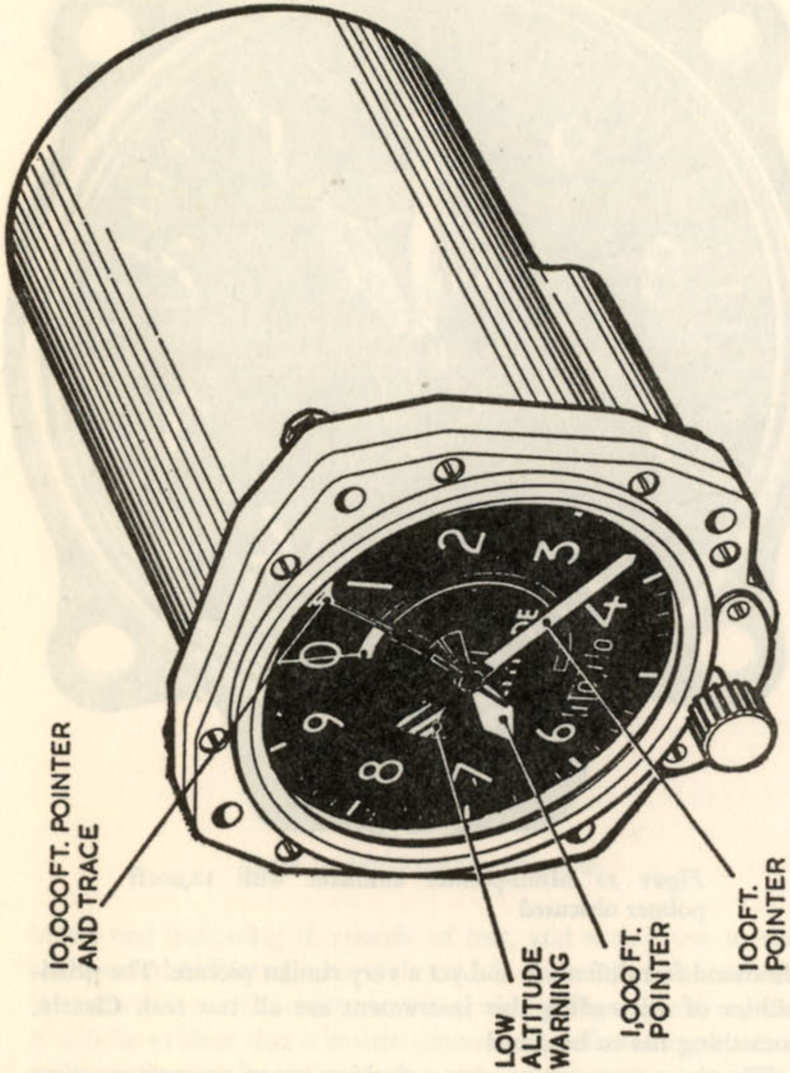


Figure 21 Modern multi-pointer altimeter

below 10,000ft and it will not go out until pressed. Efforts were later made to improve the readability of the sensitive altimeter, such as by cutting a hole in the broad thousands of feet pointer through which the little tens of thousands pointer could be seen. Then the little pointer was moved out to crawl like a bug round the edge of the dial and, lest it might still be lost to sight, it was made to leave a trace like a snail to show how far it had been. Also, a large striped flag crept into view as the aircraft descended through Flight Level 100 to remind the pilot that there is where most of the mountains are to be found! The ultimate in this line of development is shown in Fig 21.

The real solution was to use electrical power to enable the capsule to drive digital counters in what was called the servo-altimeter and to have a standby sensitive altimeter nearby for use when the electrics fail. All that is really needed, at first sight, is a clear statement of altitude and the pressure setting in use thus:

$\boxed{24{,}000}$ feet

$\boxed{1{,}013}$ mbs

but there is something very telling about the old familiar pointer moving round a dial. The angular difference of position of the pointer from one glance to the next is very eye-catching, and the direction and rate of movement of the pointer is a clearer indication of change than moving counters can give. The pilots voted to retain these features in the modern altimeter and so there arrived the form in use today (Fig 17). With the digits there can be no real excuse for misreading, and there is also the hundreds pointer from the old display now repeating the last three figures of the digital presentation. With a striped FL 100 flag to cover the first digit window, when appropriate, and a coloured power failure flag in the top of the dial, most requirements have been met. The co-pilot, of course, has an identical instrument on his panel and it is fed from a separate power supply and pressure source.

For automatic landing, the need is for an altimeter capable of showing height above the ground with an accuracy of about 1ft as the aircraft nears touchdown. This is more than can be expected from an instrument operated by a capsule and set by hand, and for this degree of accuracy resort has to be made to the radio altimeter, a typical example of which can be seen on p 18.

The main interest in this instrument lies in the last 500ft of descent shown on the right-hand half of the dial. The left side of the dial registers up to 25,000ft, heights after that being beyond its useful range.

This altimeter indicates the aircraft's height above the ground immediately below it by measuring the time radio pulses take to leave aerials in the underside of the fuselage and return after reflection from the ground. A push-button is provided to test this altimeter from time to time and to check that it is telling the truth. When the button is pushed, the pointer will go to a pre-set position if all is well.

As the aircraft approaches a runway for an automatic landing, the pilot is first guided down a gentle slope by the radio beams of the approach system, and then the radio altimeter takes over at a few hundred feet to continue control of the descent. At around 60ft, it starts to execute a manoeuvre called the 'flare'. This consists of raising the aircraft's nose a little to lessen the rate of descent. The nearer the ground, the more it wants to level out the aircraft for a soft landing. In other words, 'the lower it is, the slower it sinks', so that there is no need for the pilot to see the ground at all until his wheels have touched down and he is looking around for the airport building.

6
RATE OF CLIMB

A BRIEF glance at the altimeter will show any change in height, but a more careful look is needed to discover if the aircraft is climbing or descending. To the practised eye the altimeter, by the rate at which its pointer is moving, can indicate the rate at which height is being gained or lost but this can be a difficult assessment, especially if height is changing very fast. From the early days of instruments it was realised that an accurate indication of the rate of change of height was both useful and, in certain circumstances, essential.

The instrument which provides this information is called the vertical speed indicator, or VSI to use its popular name. It is usually mounted directly below the altimeter wherever seems most appropriate. Its pointer rests on zero in a horizontal position and two scales graduated in thousands of feet per minute range away from this position. The upper scale indicates rates of climb and the lower one rates of descent.

Curiously, when it first appeared and for decades afterwards, it was simply called the rate of climb indicator, ROC, although it had both scales as we see it today. Anyone could arrange a descent, but it took a good aircraft designer to show an impressive rate of climb!

Early aircraft could be content with scales up to 2,000ft/min, giving plenty of room on the dial for widely spaced markings. With the much higher performance of later aircraft, it was necessary to produce scales of up to 4,000 or 6,000ft/min which would

tend to crowd the dial. To overcome this problem, the scales were arranged to be non-linear, ie, expanded in the 0–1,000ft regions and progressively more cramped toward the higher ends of the scales. The precise rate of change at the higher figures is of little importance, while at small rates of climb or descent it is helpful to have a sensitive pointer which provides a large movement for quite a small change of rate.

This instrument can be useful in helping the pilot to maintain a chosen altitude. The main task is to keep the altimeter reading constant but, since this means neither climb nor dive, it follows that the VSI pointer must be kept on zero. This should enable the

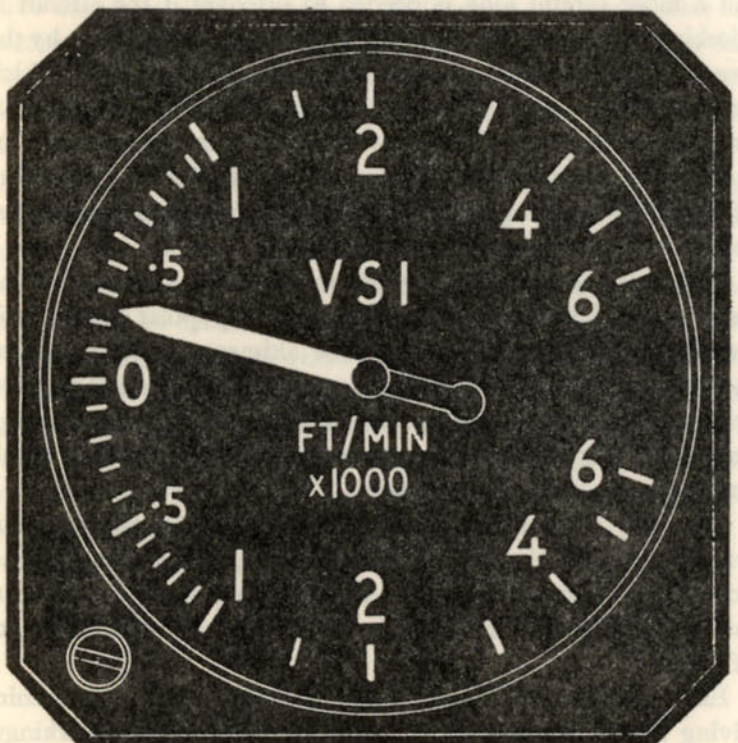


Figure 22 Vertical speed indicator

pilot to keep a tighter hold on altitude, particularly with a somewhat sticky altimeter movement.

A delicate indicator with a centre zero on which the pointer spends most of its time should be exactly true at this point, whatever the accuracy at other points on the scale. It could be irksome to find that during flight at constant altitude, or even sitting on the ground, the wretched pointer would indicate a slight climb or dive. To ensure that such a fault can be easily remedied, there is a small adjustment screw at the edge of the dial. The instrument specialist can make any necessary adjustment without removing the instrument from the panel but anyone else who dares touch it is likely to receive no mean rocket!

Operation of the VSI pointer is achieved by means of an expanding capsule with an accurately controlled leak (Fig 23). The inside of the capsule is connected by a pipe to one of the static pressure vents on the side of the aircraft. With this arrangement, the air pressure inside the capsule should always be the same as the pressure outside the aircraft. As with most pitot/static system indicators, the instrument case is sealed air-tight so that cabin pressure cannot leak in. In the VSI, however, the capsule leak allows outside air pressure to occupy the case also.

When the aircraft is not changing height, pressures on both inside and outside the capsule will be equal. There will be no difference of pressure across the capsule to expand or contract it, so the pointer will be allowed to rest on zero. As the aircraft climbs, it will experience a reduction of outside air pressure and the pressure inside the capsule will rapidly reduce accordingly. The air pressure in the case cannot reduce so readily because the air trapped in the case can only escape through the leak provided. This creates a difference of pressure which will contract the capsule to push the pointer up the scale where it will indicate a climb. The greater the rate of climb of the aircraft, the greater the pressure differential set up, and this will move the pointer farther up the scale. On levelling off to maintain constant altitude, the case pressure can catch up to equalise with capsule pressure, so allowing the pointer to return to zero. On descent, the same

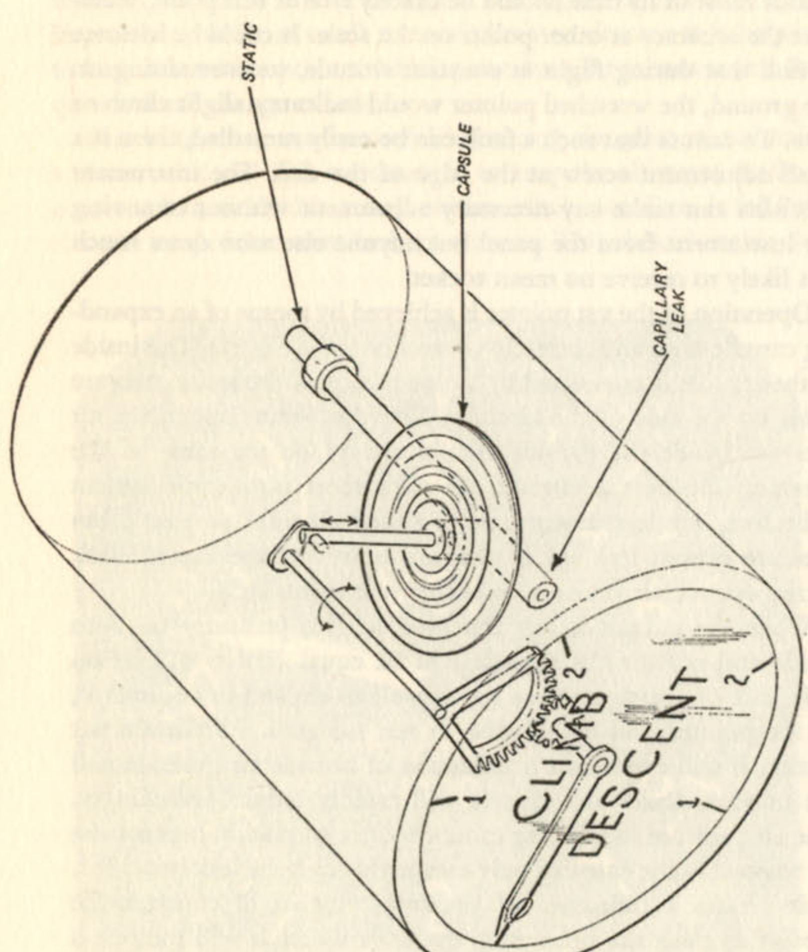


Figure 23 Vertical speed indicator mechanism. Capsule expansion or contraction occurs only when pressure round the aircraft is changing

actions occur but this time in reverse. The capsule will be expanded and the pointer will move downward.

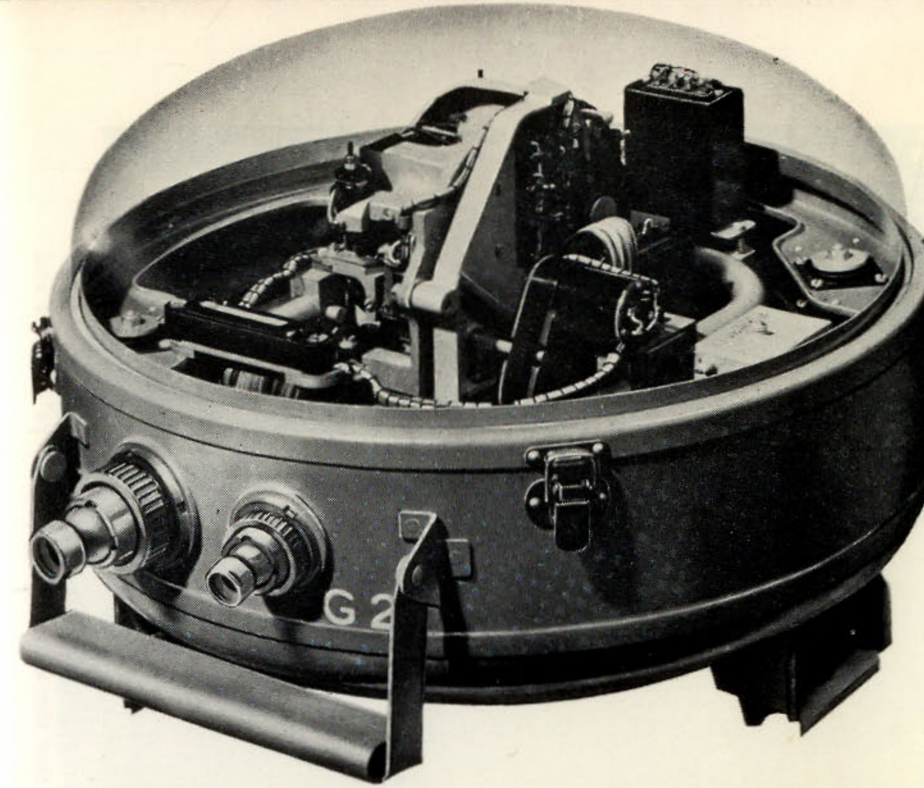
The leak, on which this instrument depends, is no mere puncture in an otherwise sound system. It is constructed with precision. Early instruments had a pattern of accurately bored jewels set in the surface of the capsule itself. Later designs have a carefully constructed leak device attached to the tube which joins the capsule. Such devices automatically compensate for temperature variation in the instrument and the reduced air pressure at altitude.

7
MACH NUMBER

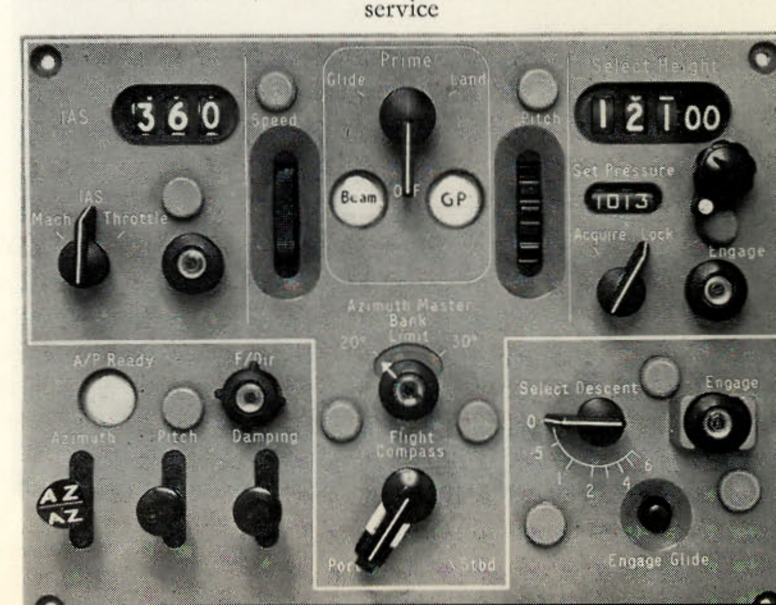
An aircraft in flight disturbs the air ahead of it. It compresses the air it meets, so forming pressure waves which travel forward, tending to prepare the air ahead for the aircraft about to meet it. The pressure waves travel at the speed of sound and so give a reasonable advance warning when the aircraft is flying slowly. When travelling at the speed of sound, however, the aircraft has caught up with its own bow waves and they cannot get out of the way. They then sit on the aircraft structure as a fairly solid pattern of shock waves which alter the characteristics of the basic shape. The effects begin to be felt from about two-thirds of the speed of sound, and sub-sonic aircraft are designed to fly up to speeds at which these effects do not cause difficulties in control. The supersonic aircraft, with a large measure of sophistication in design, copes with the changing pattern of shock waves with hardly a tremor.

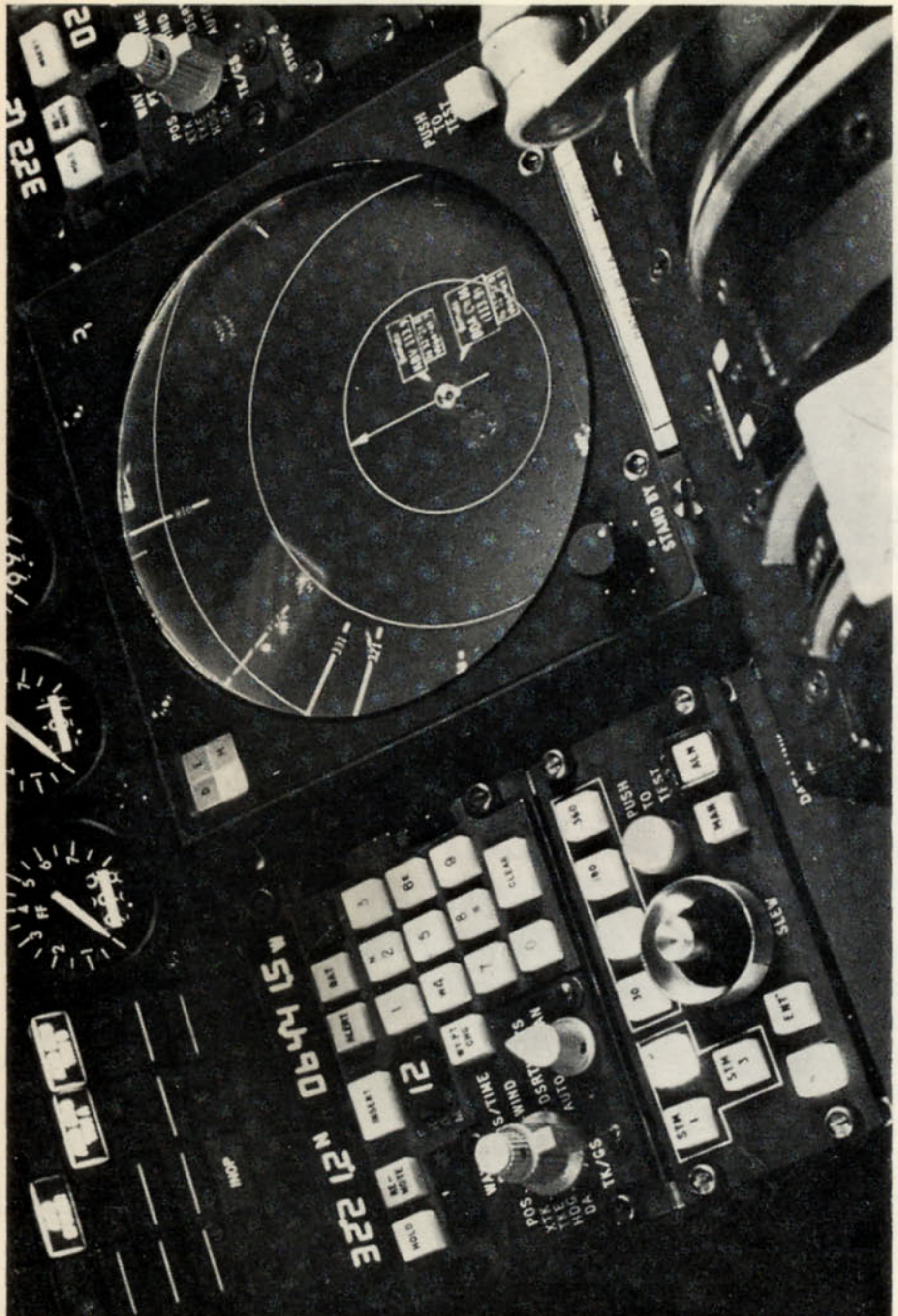
On both types, however, it is important to know the relationship between the speed of the aircraft and the speeds at which such effects occur. The speed of sound is used as a datum and given the quantity 1·0 on the scale. This is known as the Mach scale in honour of Ernst Mach, the Austrian physicist and psychologist. It is always expressed in decimal form, the Mach number at any time being related to the local speed of sound.

The speed of sound in the atmosphere varies with the relationship between pressure and density. This relationship, at any altitude, is determined by air temperature. As air temperature in



Page 71 (*above*) The gyro unit which forms the heart of the Smiths SEP2 autopilot, installed in many types of aircraft. The central cluster of three-rate gyros stays vertical to the earth's surface while the aircraft manoeuvres around it; (*below*) the flight controller of the Smiths flight control system as fitted to Trident aircraft. This system includes the SEP5 autopilot, the first to achieve automatic landing in passenger service





Page 72 Inertial navigation control and display unit together with an automatic chart display on a BOAC jumbo jet. The position readout indicates that the aircraft is at latitude 32° 21·2′ N and longitude 64° 41·5′ W

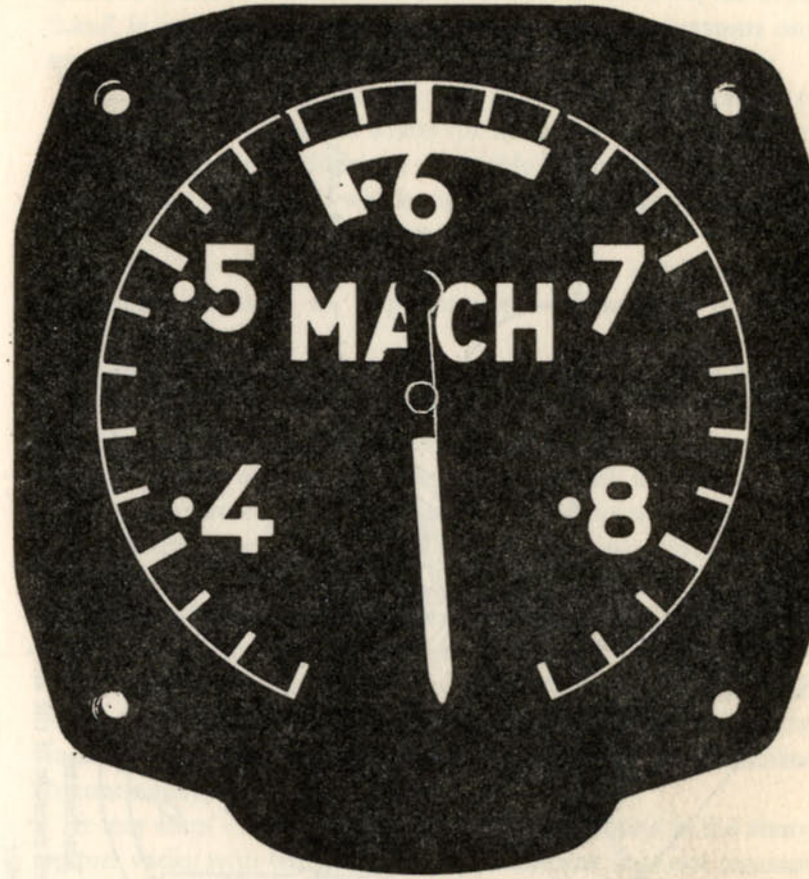


Figure 24 Machmeter. This instrument measures aircraft speed in relation to the local speed of sound at any altitude

the atmosphere varies with altitude, then so also will the speed at which a particular Mach number is reached. At the sort of temperatures met at sea level, the speed of sound is 660 knots (nautical miles per hour) while, at 36,000ft, it is about 573 knots. Above that altitude (known as the tropopause) the temperature is assumed to remain constant for quite a way up, and so also is the

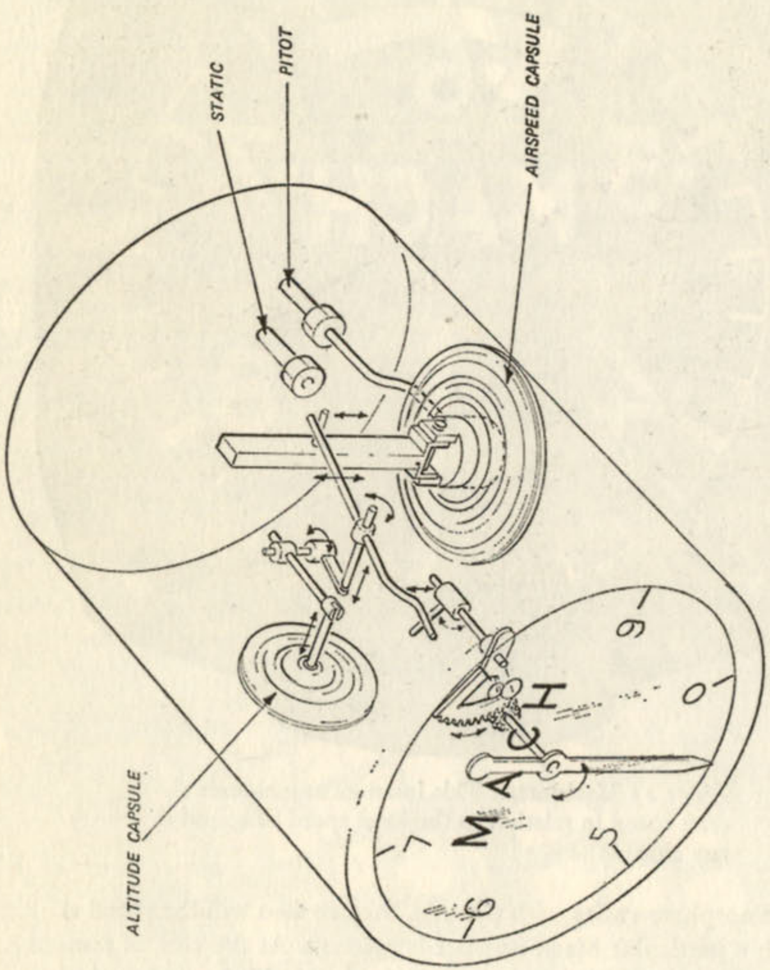


Figure 25 Machmeter mechanism. This instrument uses a combination of the speed capsule of the airspeed indicator and the aneroid capsule of the altimeter

speed of sound. In speaking of Mach number, therefore, the word 'local' is important. We are speaking of the ratio between our speed and the local speed of sound.

The instrument used to display this ratio is called a Machmeter. Fig 24 shows a typical dial where the markings are clearly shown as decimals. It also includes an adjustable lubber mark which can be set to any Mach limit which must be observed for a particular aircraft type. The setting screw for the lubber mark is usually covered up by the panel when the instrument is installed so that adjustment of such an important speed limitation is never casually made.

The mechanism of the Machmeter (Fig 25) can be said to be a combination of airspeed indicator and altimeter. It contains two capsules; a differential pressure capsule expanding with increase of airspeed and an absolute capsule expanding with increase of altitude. These two capsules work on mechanical linkage to drive the single Machmeter pointer round its scale. The instrument is connected to the pitot/static system by two tubes; one feeding pitot pressure to the inside of the airspeed capsule and the other feeding static pressure to the case. With an increase of airspeed, the airspeed capsule will increase the reading of the pointer on the scale. With an increase of altitude, the altitude capsule will reduce the reading somewhat. Working together in this way, Mach number is continually indicated.

It may seem a little odd that, as the speed of sound in the atmosphere varies with temperature, the instrument does not measure air temperature in arriving at its conclusions. It must be remembered, though, that the indication is only a ratio and that the temperature affecting the measurement of airspeed is also affecting the speed of sound. In the calculations the two effects cancel out, leaving us with just the pitot and static pressures on which to work.

It has been found possible to combine the airspeed indicator and the Machmeter in a single instrument, thereby saving space on the panel. Such an instrument is shown in Fig 26. In this design, a pointer moves round an airspeed scale calibrated in knots, while a

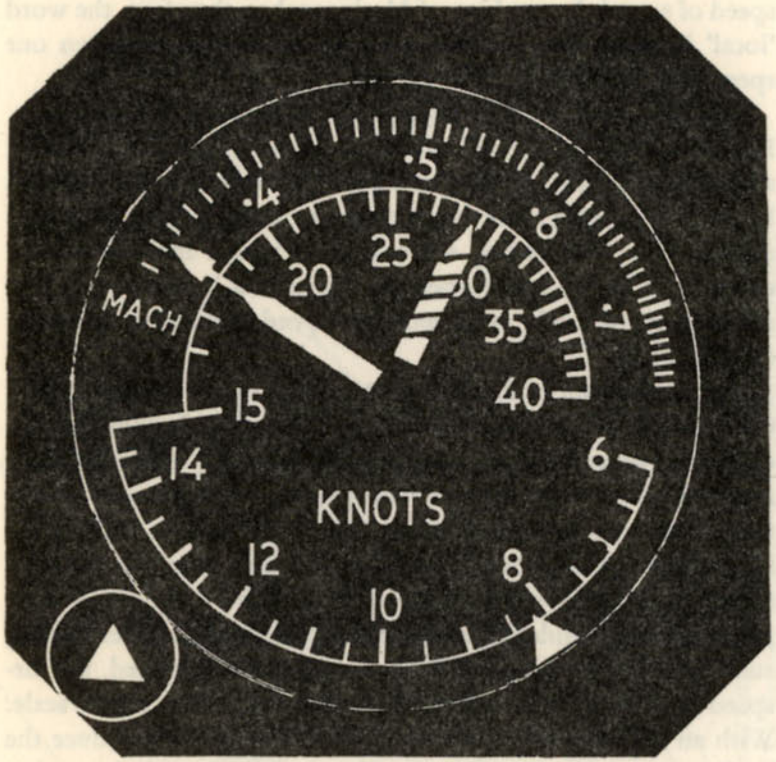


Figure 26 Mach/airspeed indicator. A space-saving design combining two instruments in one dial. It allows a single maximum speed pointer to indicate either Mach or airspeed limitations

moving Mach scale aligns itself with the end of the pointer to indicate Mach number. Thus, a single pointer can indicate both quantities.

A striped speed limitation pointer pre-set on the airspeed scale gives the pilot an indication of the maximum airspeed at which the aircraft is permitted to fly. As the Mach number increases, the Mach scale will pick up the striped pointer and hold it to maximum Mach number for the aircraft. At the higher altitudes, this

will be at a lower than maximum airspeed so the pointer will be carried down the airspeed scale. By keeping the indicating pointer lower than the striped pointer, the pilot is keeping the aircraft within both limits at all times.

8

THE FLIGHT DIRECTOR

To assess the condition of a complex system, it is usually necessary to scan a number of dials. When that system is a large vehicle moving in three dimensions at considerable speed, frequent scanning is required if any assessment of the situation is to be valid and useful. The task of controlling the aircraft might be described as responding to changes of various quantities and applying corrections to restore those quantities to a chosen datum. The sheer business of looking from one dial to another and applying control which will affect other dials which were previously all right, and then applying further control to correct these also, is a fascinating fairground game calling for considerable acquired skill. As a regular occupation, however, it can become tedious and, in times of stress, downright difficult. The problem calls for automation of the basic tasks and some collective output from the various indications involved. It is not enough simply to place all the required indicators side by side in a central group.

One answer would be to have a central indicator which would repeat what is wrong with each of the others in the group. A better answer is to have one central indicator which tells, not what is wrong, but simply what to do about it. Such an indicator is called the Flight Director.

The flight director is usually found in the form of two crossed pointers superimposed on the artificial horizon display. The system may comprise a number of black boxes, including a computer and switching circuits by means of which a variety of opera-

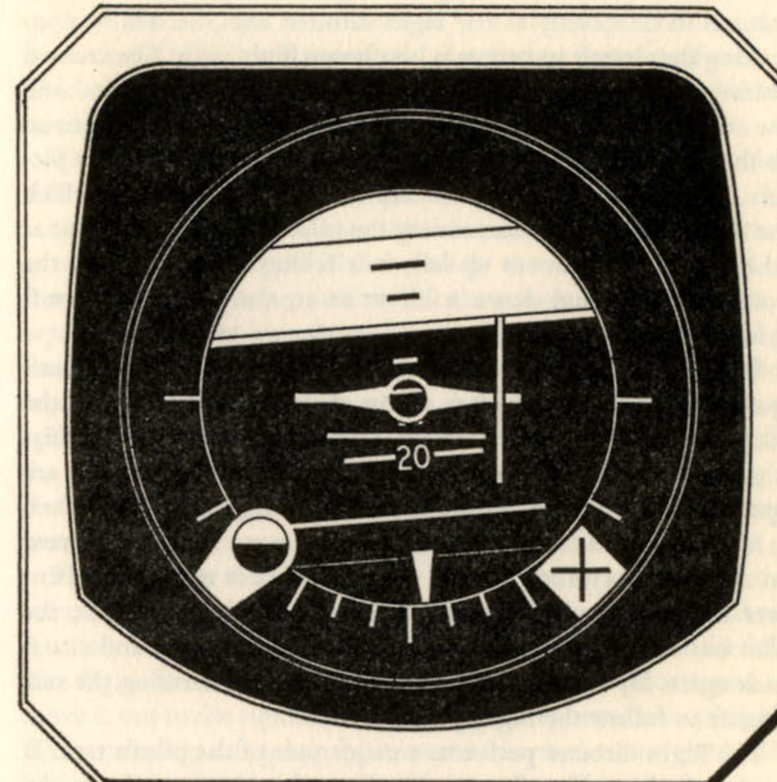


Figure 27 Director horizon. Flight director commands are displayed against the horizon background for basic reference

tional modes may be selected. The two little pointers may not be much to look at but their behaviour is the result of a careful mixture of information from various sources. It is the task of the flight director computer to receive the same information as can be seen on the instruments of the flight panel and to decide what needs to be done to control the aircraft. Its decision is displayed by the crossed pointers in the form of four simple commands: UP, DOWN, LEFT or RIGHT, or any sensible combination of these. If the

pilot chooses to obey these commands and moves the control column to do exactly as the flight director says, he will be controlling the aircraft to maintain his chosen flight path. The crossed pointers are always at right angles to each other; one vertical and the other horizontal. Each can move across the face of the horizon so that the point at which they cross can be anywhere in the picture. The position of that point represents the direction in which the flight director is commanding the pilot to aim. If the point at which they cross moves up left, it is telling him to pull up the nose with left hand down a bit so as to aim the little aircraft symbol towards the cross.

Even though, as described in Chapter 1, the little aircraft symbol is stuck to the glass of the dial and cannot move, the correct approach to adopt is to imagine that one is going to 'fly' it on to the cross and then keep it there. When the controls are operated to get the real aircraft aimed in the right direction, what, in fact, happens is that the crossed pointers move so that they cross on the aircraft symbol. This is the result that is required. Whenever the aircraft symbol appears to wander from the cross, the pilot has only to obey the simple command displayed and aim it back again. By keeping it there, he will be manoeuvring the real aircraft to follow the flight path selected.

The flight director performs a major part of the pilot's task. It receives information from a number of sources, analyses the situation and decides the action required to control the aircraft. Whereas the pilot collects such information by scanning a number of dials in turn, the flight director can receive information from all the necessary sources at the same time and respond instantly to changes in any of them. It is literally able to look in all directions at once. When dealing with such a system the word 'error' is very frequently used. Error, in this context, does not mean some drastic mistake but merely a deviation from some normal condition. While the aircraft is exactly following some pre-determined flight path, all errors are zero. The flight director computer will not produce any output signals and the crossed pointers will come to rest crossing exactly on the aircraft symbol in the centre of the

dial. When the aircraft drops a wing, wanders off heading, slides out of the centre of a radio beam or loses altitude, an error signal is produced which will move the appropriate pointer off centre. This calls for corrective action which will restore the former condition and reduce the error signal to zero.

The basic function of the system is to give commands which will enable the pilot to keep the aircraft straight and level. To achieve this, it must have basic attitude information from a vertical gyro fed in at all times. This is exactly the same information as that displayed by the artificial horizon but it comes from a separate gyro. The signals are arranged so that no error signal is produced when the aircraft is level in pitch and roll. Another input to the system is magnetic heading from the compass system. This is arranged so that no error signal is produced while the aircraft remains on the same heading as when the flight director was switched on, or from any other heading which may later be selected.

To appreciate the action of the system, let us assume that the aircraft has wandered from the datum heading just described. Assume that the nose of the aircraft has swung round to the left. The flight director vertical pointer will receive an error signal to move it out to the right, thus displaying a command to turn right. To turn the aircraft properly, it must be banked to the right and, in doing this, another error signal is introduced because the wings are no longer level. At a certain bank angle, these two error signals will be equal and cancel each other out, so allowing the pointer to return to centre. While it is central, all is well. The aircraft is banked and turning to the right; back toward the original heading. As it approaches the original heading, the heading error signal is reducing, leaving the bank signal to move the pointer out to the left. Moving the aircraft controls to the left will level up the aircraft as it settles onto the correct heading. This accurately performed manoeuvre is achieved merely by following the commands of the vertical pointer and moving the aircraft controls left or right as directed.

In the same way, deviations in pitch can be corrected by follow-

ing the commands of the horizontal pointer. It is not necessary to know the extent of the deviation but merely the action necessary to resume the correct flight path.

A system which determines precisely how an aircraft should be manoeuvred must be extremely reliable in its operation. It must never be allowed to give commands which, when obeyed, would place the aircraft in an unsafe position. If the flight director, through some fault, calls for more and more control in one direction, there must be some warning to ignore it before the aircraft ends up flying inverted! The system, therefore, is continually looking for faults within itself and in the information fed to it. When a fault is detected, a prominent warning flag will spring into view and the system's commands must then be ignored. Even this safeguard, however, is not enough. However sophisticated and reliable a warning device may be, it must be assumed in the interest of safety that one day, perhaps, a serious fault may occur without giving any warning. The pilot, in order to recognise such a situation, must never allow his attention to focus on the flight director to the exclusion of all other indications. He must be in a position to know that the flight director commands he receives are reasonable and justified, and this means scanning the other instruments on the panel.

The most important indication of all is given by the artificial horizon, and this forms the background against which the flight director is seen. There can be no excuse for rolling the aircraft on its back in response to a failed director while the horizon is clearly showing what is happening. The director receives its attitude information from its own separate vertical gyro so that no fault can affect both indications. This knowledge of 'which way is up' is the primary information supplied to the flight director system and without which the system is useless. All other inputs to the system are in opposition to the pitch-and-roll attitude inputs. These other inputs include magnetic heading, altitude, airspeed, Mach number, vertical speed, and radio navigation. One or more of these quantities can be kept constant by selection of knobs on instruments or control panel and following the flight

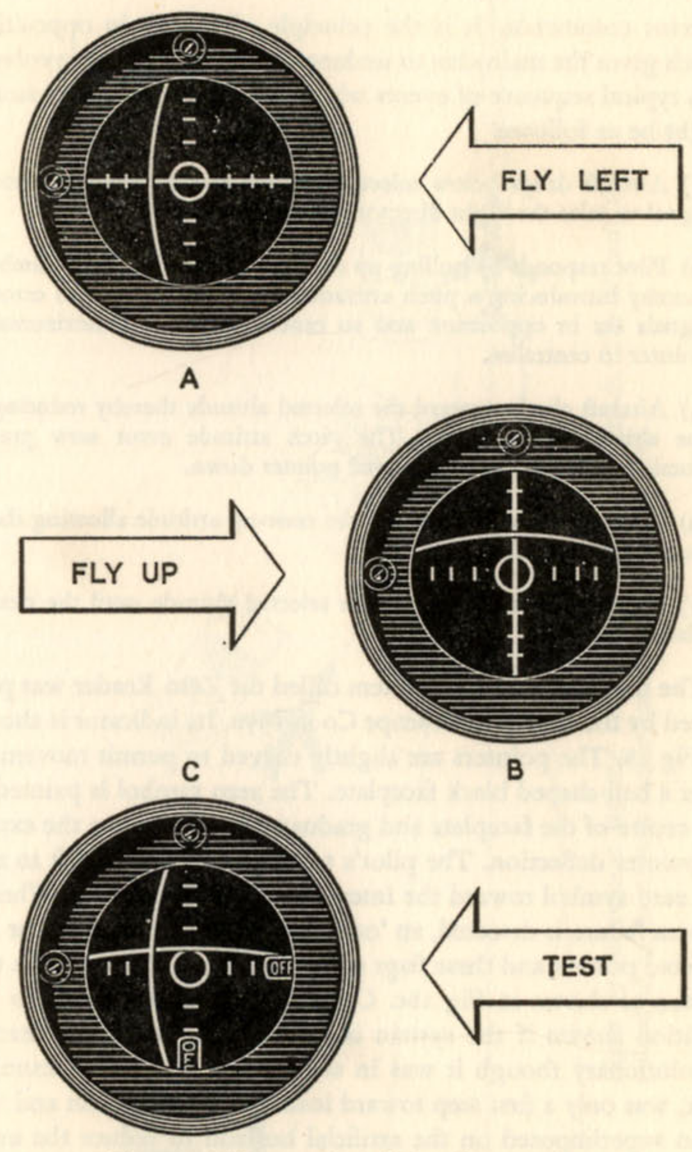


Figure 28 Zero-reader flight director indicator. Flying to aim the circle at the intersection of the two pointers will guide the aircraft on to the selected flight path

director commands. It is the principle of signals in opposition which gives the main clue to understanding the process involved.

A typical sequence of events while selected to 'ALTITUDE HOLD' might be as follows:

(1) Aircraft drops below selected altitude causing altitude error signal to raise the flight director horizontal pointer.

(2) Pilot responds by pulling up the nose of the aircraft to climb, thereby introducing a pitch attitude error signal. The two error signals are in opposition and so cancel, leaving the horizontal pointer to centralise.

(3) Aircraft climbs toward the selected altitude thereby reducing the altitude error signal. The pitch attitude error now predominates driving the horizontal pointer down.

(4) Pilot responds by reducing the nose-up attitude allowing the pointer to centralise.

(5) Aircraft resumes flight at the selected altitude until the next disturbance.

The first flight director system called the Zero Reader was produced by the Sperry Gyroscope Co in 1950. Its indicator is shown in Fig 28. The pointers are slightly curved to permit movement over a ball-shaped black faceplate. The zero symbol is painted at the centre of the faceplate and graduated marks denote the extent of pointer deflection. The pilot's task is to fly his aircraft to aim the zero symbol toward the intersection of the pointers. When a system failure is detected, an 'OFF' flag springs into view near the affected pointer and these flags can be displayed on pressing a test button as shown in Fig 28c. On test, the pointers move to the position shown if the system is serviceable. The Zero Reader, revolutionary though it was in simplifying the pilot's scanning task, was only a first step toward instrument integration and was soon superimposed on the artificial horizon to reduce the ever-increasing number of dials which were tending to clutter up the instrument panels.

The most exacting task performed by flight director systems is

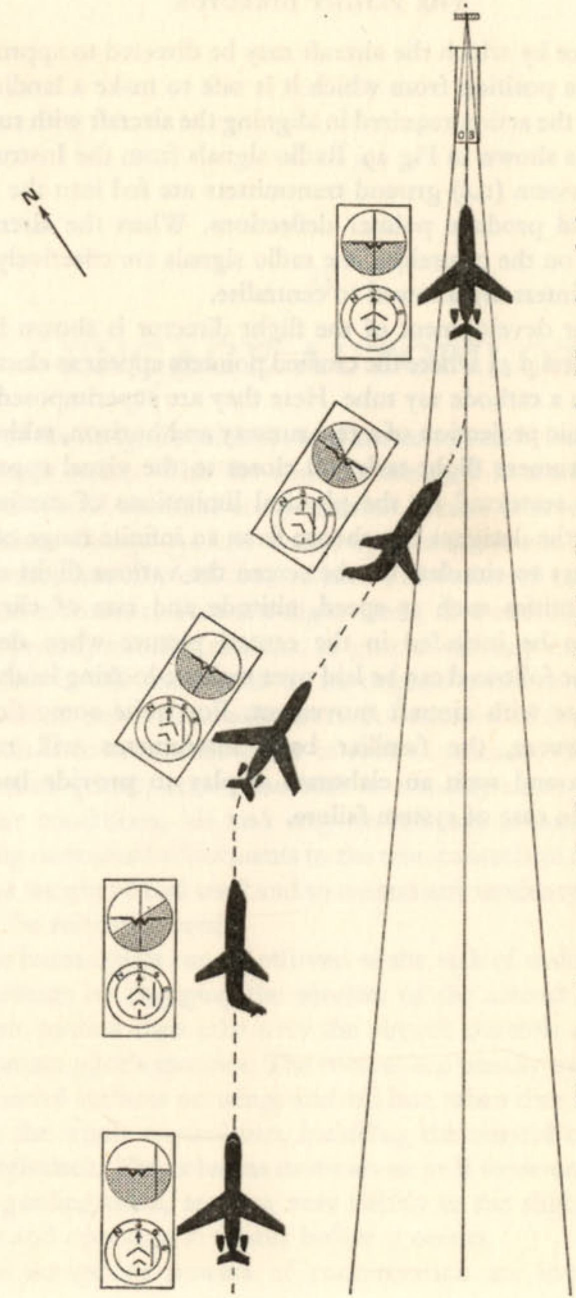


Figure 29 Instrument landing system (ILS) localiser approach. The aircraft is guided on to the runway centre-line by radio beam patterns

the guidance by which the aircraft may be directed to approach a runway in a position from which it is safe to make a landing. A diagram of the action required in aligning the aircraft with runway centreline is shown in Fig 29. Radio signals from the Instrument Landing System (ILS) ground transmitters are fed into the flight director and produce pointer deflections. When the aircraft is positioned on the centreline, the radio signals are effectively zero and the pointers are allowed to centralise.

A further development of the flight director is shown in the illustration on p 53 where the crossed pointers appear as electronic symbols on a cathode ray tube. Here they are superimposed on a photographic projection of a real runway and horizon, taking the pilot's instrument flight task still closer to the visual approach. No longer restricted by the physical limitations of mechanical indicators, the designer can choose from an infinite range of possible displays to simulate on the screen the various flight conditions. Quantities such as speed, altitude and rate of climb or descent can be included in the central picture when desired. Tracks to be followed can be laid over realistic-looking landscapes which move with aircraft movement. For quite some time to come, however, the familiar basic instruments will remain clustered round such an elaborate display to provide back-up indication in case of system failure.

9
ENGAGE AUTOPILOT

ONE of the design requirements of the aeroplane is that it shall be inherently stable. With the controls trimmed to a suitable position, it should continue to fly without human intervention until conditions change. As fuel is used up, it will become lighter and, given the same lift, will tend to rise. The fuel used may alter the balance of forces and cause a slight climb, dive or roll, but, over a short period, stability remains. A gust of air may toss it over a little but it will settle back to its original position after a few oscillations, rather like a ship at sea. A basic task of the man at the controls is to reduce the effect of such disturbances by applying control to quickly return the craft to a steady state. Cruising in still air conditions, his task may be reduced to one of merely making occasional adjustments to the trim controls to compensate for the weight of fuel used and to correct any tendency to wander from the selected course.

The human pilot can be relieved of the task of making control movements by engaging the services of the aircraft Autopilot. Electric motors then take over the aircraft controls and replace the human pilot's muscles. The motors are usually sited close to the control surfaces on wings and tail but, when they move, they move the whole control run, including the control columns on the flightdeck. The columns move about as if some unseen hands were guiding them, reacting very swiftly to the slightest disturbance and opposing it almost before it occurs.

The autopilot's powers of concentration are impressive. It

never seems to miss what is going on and it can keep a very tight control of aircraft movement for hours on end without showing any signs of fatigue or slackening of response. It does not know about boredom and is not at all concerned with how long it takes to arrive anywhere. It is quite devoted to its task and never suffers emotional upsets. Of course, it has its off days but it then usually warns that something is amiss and can readily hand back control to the human pilot before things become confused. With its endless capacity for drudgery, it is a most useful servant on any flight. The human pilot, relieved of routine tasks, can concentrate on other things such as communication with air traffic control centres on the route, the weather situation ahead, and all other details of flight progress.

It is necessary at intervals during the flight to check that the autopilot is coping with what it is required to do. On aircraft where the flight director system is sufficiently independent of autopilot sources of information, it is useful to see that the autopilot is managing to keep the flight director nicely centred. This gives a good indication that all is well. Another important check, however, must be made. It concerns the trimming of the aircraft controls for hands-off flight.

In manual flight, the pilot will not often sit and hold the control column in a position which will fly the aircraft in the way he requires. Instead, he will operate the aircraft trim controls so that, hands-off, the control column will stay in the position needed. The autopilot, however, is quite happy to hold the controls under load for any length of time while maintaining the required flight path. This would be all right until the autopilot was disengaged, when the controls would suddenly spring back to their normal position leaving the aircraft out of trim. Worse still, if the autopilot were to disengage itself unexpectedly, the departure of the aircraft from its flight path might add an element of alarm to the situation. It is obviously necessary then to check that, although the autopilot is engaged, the aircraft is nevertheless in a trimmed condition. The old method of doing this was to disengage the autopilot, trim the aircraft and then re-engage. Later it became possible to

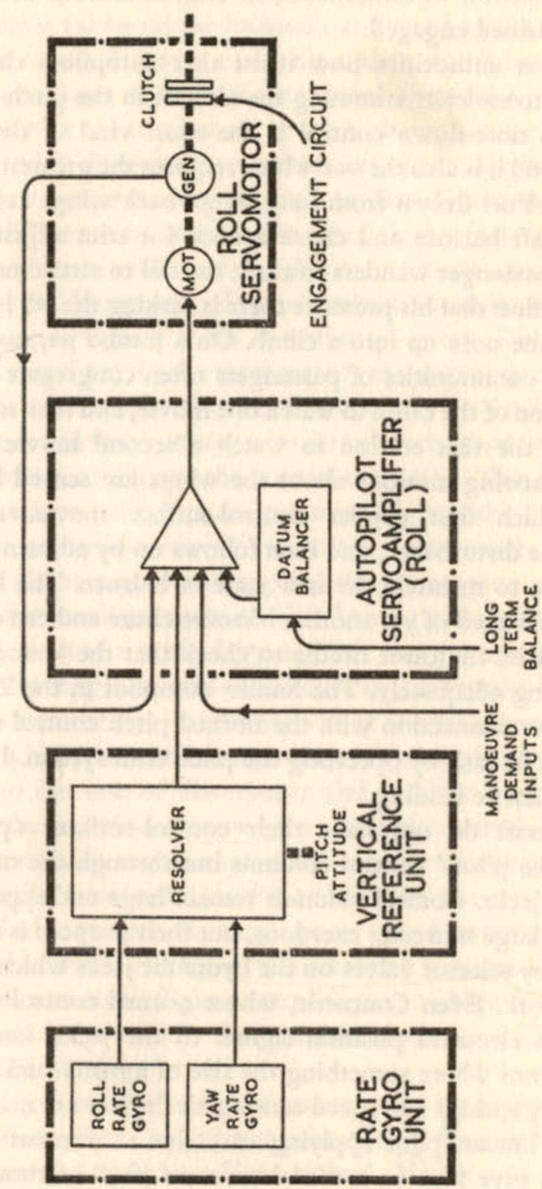


Figure 10 Autopilot roll channel

set the trim controls to centralise some trim indicators while the autopilot remained engaged.

The aviation authorities now insist that autopilots shall be capable of automatically trimming the aircraft in the pitch sense. This nose-up nose-down control is the most vital of the trim adjustments and it is also the one which requires the greatest range of operation. Fuel drawn from long swept-back wings can alter the fore-and-aft balance and create a need for trim adjustment. Each time a passenger wanders towards the tail to attend nature's call, he can reflect that his presence there is making the tail heavier and putting the nose up into a climb. On a jumbo jet, not fully loaded, large communities of passengers often congregate in the forward section of the cabin to watch one movie, and then migrate en masse to the rear section to watch a second movie. Such gigantic see-sawing motions about the wings are sensed by the autopilot which first applies control-surface movements to counteract the disturbance, and then follows up by adjustment of the pitch trim to maintain the new state of balance. The human pilot is thus relieved of yet another irksome chore and can simply observe the trim indicator needle to check that the 'automatics' are functioning adequately. The Smiths autopilot in the Trident aircraft has no connection with the normal pitch control system but performs its task by operating the pitch trim system. Its task includes automatic landing.

Large aircraft do not have their control-surfaces operated directly by the pilots' control columns but through the medium of hydraulic jacks. Control columns remain large and apparently intended for large muscular exertions, but their purpose is merely to operate tiny selector valves on the hydraulic jacks which do all the heavy work. Even Concorde, whose normal control system merely sends electrical position signals to the jacks, has large control columns where something the size of a matchstick might suffice. Heavy springs and speed-sensing air devices are needed to prevent the human pilot applying excessive movement to the controls and give him an artificial sense of 'feel' as though he really were physically moving the controls against the airflow.

The autopilot in a power-controlled aircraft merely operates the selector valves on the hydraulic jacks and so does not need to be very strong. It leaves the hydraulics to do all the heavy work while it assumes the role of director of operations.

Correction of disturbances to the flight path is the basic task of an autopilot. It is a servo-mechanism, meaning that it applies control movement proportional to the disturbance which it senses. The sensing unit is a cluster of three gyroscopes mounted with their axes in different directions: one in roll, one in pitch and one in yaw. Movement of the aircraft about these axes will produce output signals from the affected gyros. The signals are amplified and sent to the servomotors to apply corrective control-surface deflection. As the aircraft returns to its previous attitude, the gyros will sense an opposite disturbance which will cause the servomotors to remove the control deflection. This should allow the aircraft to settle back to its normal flight path.

Early autopilots simply measured how much the aircraft rotated about a gyro and applied the appropriate control. This meant that small amounts of disturbance produced small control deflections, and a really large aircraft movement was needed to produce enough control deflection to really take effect. Later designs measure not just the amount of aircraft movement but the rate at which it moves. In this way, it can apply control proportional to the rate of disturbance and produce large corrections before the aircraft has moved very far from normal. It appears to apply control in anticipation of the actual requirement.

Autopilots are not a recent addition to the range of devices available for aircraft. As long ago as 1909 Lawrence Sperry, son of the founder of the Sperry Gyroscope Co, started the development of automatic flight control devices in New York. In 1912, he installed the world's first automatic pilot in a Curtiss flying-boat. (Picture, p 54.)

In May 1914, at the age of twenty-two, he competed in Paris for a French War Department prize of fifty thousand francs for 'a device contributing to flight safety'. He won the prize in a spectacular demonstration of his automatic pilot by flying low

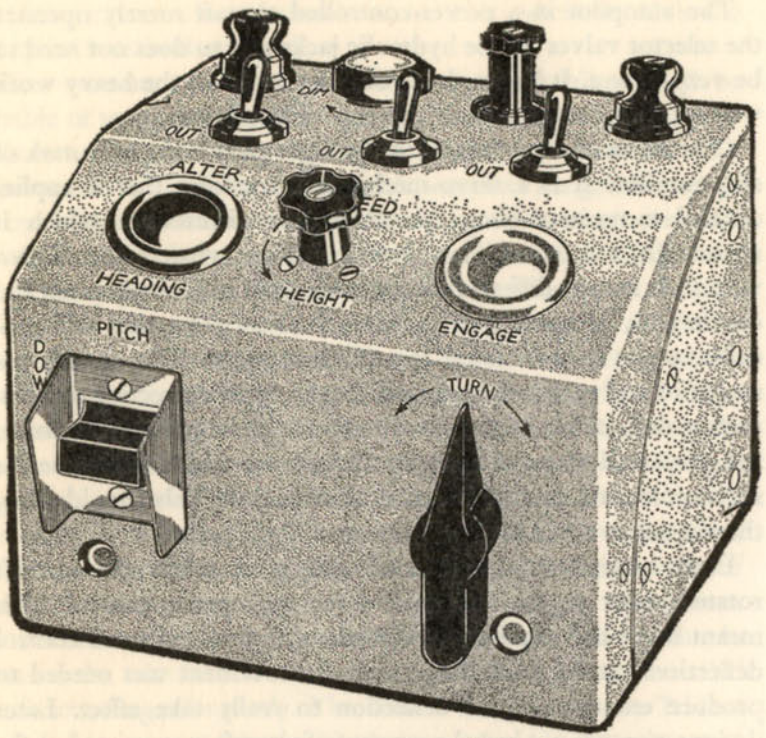


Figure 31 Autopilot controller. This box, mounted on the central console between the two pilots, is used to engage the autopilot and select its various operating modes

past the onlookers holding his arms high above his head while his mechanic walked to and fro between the biplane's wings. The aeroplane maintained its level flight attitude and suitably impressed the judges. Years later, Sperry autopilots were in use with aircraft operators all over the world.

For many years, the autopilot has been thought of as having something of a personality rather than as mere hardware. It has been affectionately known as 'George' by many people, both aircrew and passengers, perhaps because of its robot-like activities. The visitor to the flightdeck, on asking to see the autopilot, can

only be shown the controller and perhaps a few minor indicators and warning devices. The Smiths SEP2 controller is shown in Fig 31. On it are electrically interlocking selector knobs and switches enabling the human pilot to signal his requirements into the electronic boxes of the autopilot. This autopilot has been installed in many aircraft types including the De Havilland Comet, the world's first jet airliner. Its gyro control unit with transparent plastic cover is illustrated on p 71. A later Smiths autopilot, installed in Trident aircraft, uses the controller shown in the illustration lower. This autopilot, the first to perform automatic landings in passenger service, has its controls set out in the Basic-T pattern used on the flight instrument panel. Speed controls are at top left, altitude controls at top right, directional controls at lower centre and, at the top centre, pitch attitude and landing mode switch. Rate of descent can be selected at lower right, while at left are the three levers which are used to selectively engage control about the three aircraft axes.

Subsequent design trends took the autopilot controller out of its familiar location on the console between the two pilots and placed it on the glareshield above the instrument panels just below the centre windscreens. This location produced the requirement for long narrow controller layouts as in Tristar and Concorde, Fig 32 (a) and (b) respectively. In both these designs, the autopilots are dual systems and are engaged by means of two levers situated at the centre of the group. Various control modes are selected by square-shaped buttons which light up when pressed. VHF navigation radio selectors are situated at both ends of these autopilot controllers, as these determine the particular ground radio aid to which the autopilots are coupled.

A feature of almost all autopilots is the cut-out button, and each pilot has one on his control column. Pressing a cut-out button will immediately disengage an autopilot and hand back control of the aircraft to the human pilot. This gives the pilot the overriding authority over anything the autopilot chooses to do.

The gyro control units of autopilots are usually below floor level, somewhere amidships and near the aircraft centre of

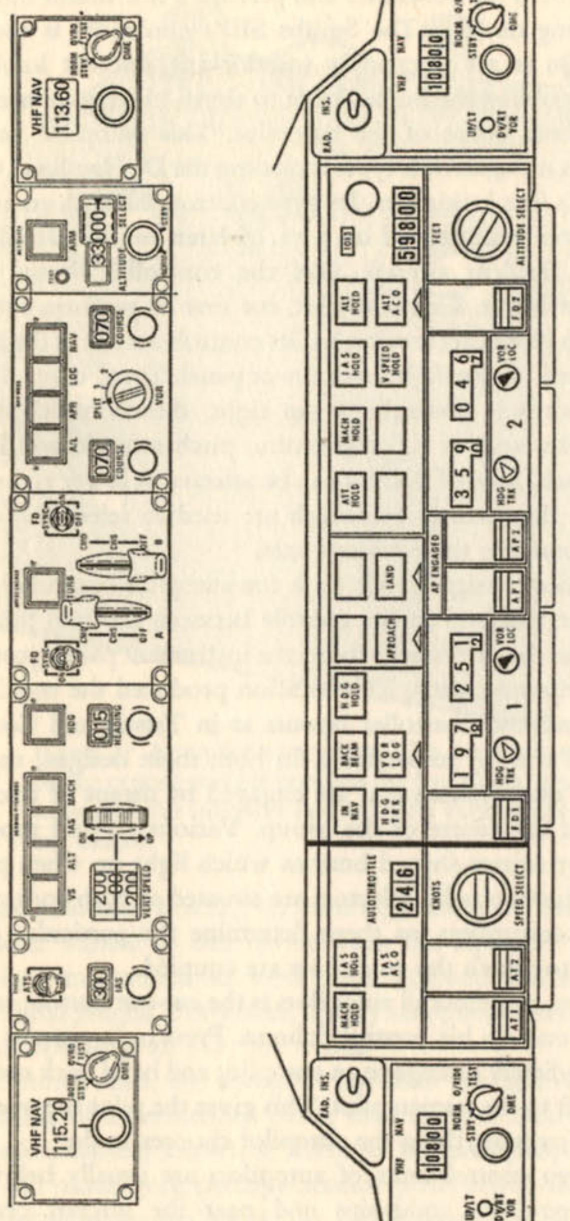


Figure 32 (*top*) Autopilot controller on Tristar; (*bottom*) autopilot controller on Concorde

gravity. Computers and amplifiers are on shelves in an equipment bay, while servomotors or similar devices are in the wings and tailplane on the controls which they operate. Nevertheless, comic inventors usually depict the autopilot as a small mechanical robot sitting on top of the dashboard working a small control column of its own with clocklike precision.

10

WEATHER RADAR

For safety and comfort during flight it is not enough to know where the aircraft is, which way up and where it is going. It is also necessary to know the weather conditions ahead of the aircraft. In daylight, the pilot who is something of a meteorologist can look ahead through the windscreen and study the cloud formations to determine where the turbulent stormy areas are. He can then navigate his aircraft to avoid them by a safe margin. At night, his ability to see the weather situation is drastically reduced and there are also times when the scene ahead is so thickly sown with squalls as to seem impenetrable. The pilot, in order to assess the situation accurately, must turn his attention to the Weather Radar screen on his panel.

The weather radar system paints on the screen a phosphorescent map of the rainfall areas ahead of the aircraft. This enables the pilot to choose a path round the areas of maximum turbulence, or between them if a gap sufficiently wide exists. In a situation where a line of storms is ranged widely ahead of the aircraft, he can determine during approach to the cloud system which areas are developing in storm size and severity and which are past their worst and decaying. Thus, where it is not possible entirely to avoid storms, at least the path of minimum disturbance can be chosen.

The screen as shown in Fig 33 represents a plan view of the area ahead of the aircraft. The aircraft itself is positioned at the bottom centre of the display. The vertical line in the centre re-

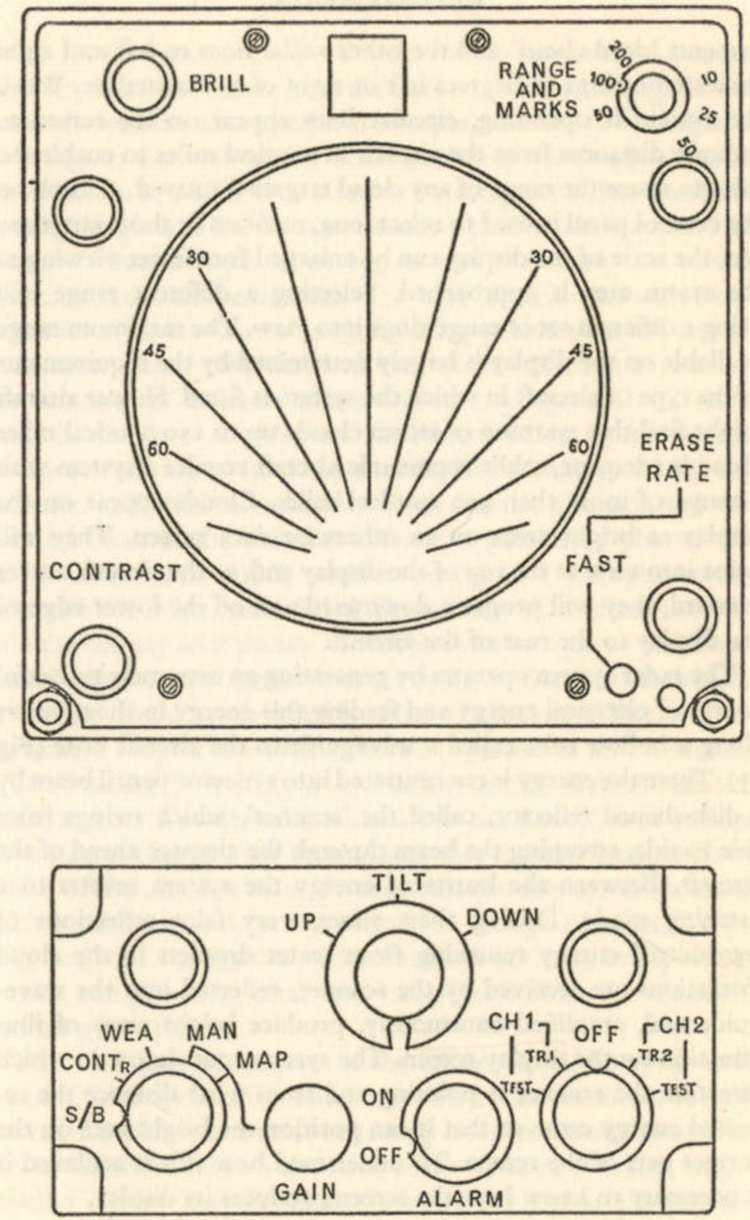


Figure 33 Weather radar indicator and control panel

presents 'dead ahead' and the other radial lines to left and right indicate bearings in degrees left or right of the centreline. When the system is operating, circular lines appear on the screen to indicate distances from the aircraft in nautical miles to enable the pilot to assess the range of any cloud targets displayed. A knob on the control panel is used to select long, medium or short ranges so that the scale of the display can be enlarged for clearer viewing as the storm area is approached. Selecting a different range will bring a different set of range rings into view. The maximum range available on the display is largely determined by the requirements of the type of aircraft in which the system is fitted. Slower aircraft might find that warning of storm clouds up to 150 nautical miles ahead is adequate, while supersonic aircraft require a system with a range of more than 300 nautical miles. Clouds appear on the display as bright areas on an otherwise dark screen. They will come into view at the top of the display and, as the aircraft moves forward, they will progress downward and off the lower edge of the display to the rear of the aircraft.

The radar system operates by generating an extremely powerful source of electrical energy and feeding this energy in short bursts along a hollow tube called a waveguide to the aircraft nose (Fig 35). There the energy is concentrated into a narrow pencil beam by a dish-shaped reflector, called the 'scanner', which swings from side to side, sweeping the beam through the airspace ahead of the aircraft. Between the bursts of energy the system reverts to a listening mode. During these times, very faint reflections of transmitted energy returning from water droplets in the cloud formations are received by the scanner, reflected into the waveguide and, amplified enormously, produce bright areas of illumination on the display screen. The system must know in which direction the scanner is pointing and from what distance the reflected energy came so that it can position the bright area on the correct part of the screen. To understand how this is achieved it is necessary to know how the screen produces its display.

As in a television tube, the radar indicator produces its picture by firing a stream of electrons at the phosphor coating on the

inside of the screen. Unlike the television, however, the radar starts by firing the electrons at the centre of the lower edge of the screen (where the aircraft is) and sweeping the line of fire radially outwards to the other edges. The direction of the sweep is tied to the direction in which the scanner is 'looking' at all times, and the flash of brightness left by the electrons persists so it appears as though a line of light is waving to and fro across the screen synchronised with the scanner. The start of each outward sweep coincides with the start of each listening period after a burst of transmitted energy. By the time each cloud reflection returns to the scanner, the electron stream will have progressed outwards from its origin to a point on the screen which represents the distance of the cloud from the aircraft. The scanner, moving on, transmits and receives reflections from another direction and the electron beam in the indicator follows to paint up a plan of the cloud distribution which persists briefly as a phosphorescent glow. Before it has quite faded, the scanner will return and update the display as it passes. Clouds are not opaque to the transmitted radar energy. Reflections are received from clouds which, to the eye, would be obscured by other nearer clouds. Thus a comprehensive map of the weather ahead is presented on the screen.

The scanner is looking at a thin horizontal slice of airspace ahead and to the sides of the aircraft as the pencil beam swings from side to side and the system sees only those reflections from a slice of the clouds ahead. To maintain the display, the scanner must continue to look at that slice even though the aircraft may pitch and roll. Stabilisation of the scanner is achieved by supplying it with compensating pitch and roll signals from the aircraft's vertical gyro systems.

That thin slice of airspace at the aircraft level, however well scanned, is altogether too narrow a view of the situation. It may not cut the widest and most menacing levels of cloud formations and it will not see clouds above or below it, some of which might develop rapidly into significant weather dangers as the aircraft approaches. To increase the scope of the system, it is provided with a tilt control knob which enables the pilot to direct the

scanner up or down to look at levels above or below the aircraft's altitude. Use of this control allows him to construct in his mind a vertical picture of the weather distribution ahead. This, coupled with his knowledge of meteorology, provides the basis for choosing the best method of storm avoidance. Weather hazards are encountered not only by flying into storm clouds but also by flying too close above, below or beside them. The radar receives its reflections only from water droplets or ice with a coating of water. It does not see water vapour or dry ice, so the pilot must miss the seen hazard by a margin sufficient to ensure that he also misses the possible unseen hazards, such as dry hailstones, which might be associated with it. Normal practice is to avoid all hazard areas by a distance of at least 5 nautical miles, and even greater distances at low temperature and high altitude.

Faced with a variety of cloud formations across his route, the pilot is provided with an additional control on the radar to show which clouds are potentially dangerous and which are relatively safe. This control is a switch position labelled 'CONTOUR'. The worst rain clouds produce the brightest images on the radar screen. When the contour mode is selected, all areas of the cloud slice above a certain signal strength are prevented from operating the display. The nastiest clouds, therefore, have dark interiors as shown in Fig 34 (bottom). This gives a contour effect and the worst weather is encountered where the effect is most clearly defined. Clouds nearby give back stronger reflections than more distant clouds, so the system takes distance into consideration when working out which clouds should show contour. Otherwise the pilot might be surprised to find that a seemingly innocuous cloud contours just before he is due to enter it. The flight situation is now somewhat clearer. The aircraft must not necessarily avoid every cloud in the sky but only those which produce the contour effect on the radar display. He can use the controls on the panel to alter the brightness of the display to suit daylight or night time viewing conditions and to alter the strength of the received signals for better discrimination between strong and weak reflections.

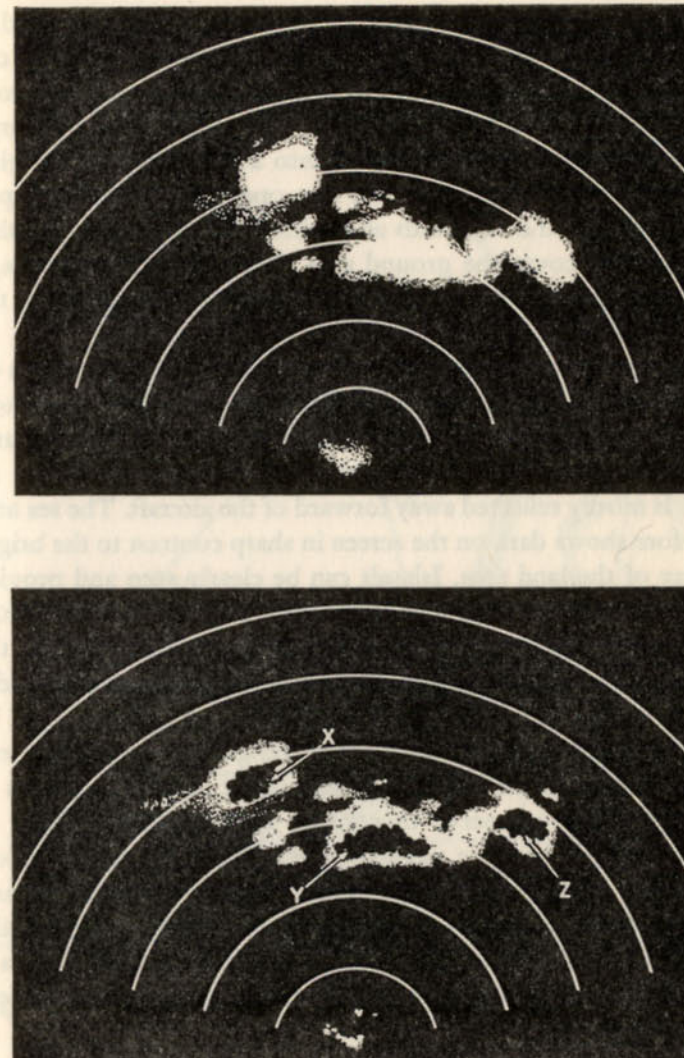


Figure 34 (*top*) Cloud display on radar screen in 'normal' mode; (*bottom*) the same cloud display with 'contour' mode selected. Areas of maximum weather turbulence within the cloud formation are displayed as dark patches at X, Y, and Z

Ground mapping is another facility afforded by the weather radar system. By selecting 'MAP' mode of operation, the pilot can see a display on the ground ahead of the aircraft as a pictorial map on the screen. To achieve this the narrow pencil beam of energy pulses from the scanner is spread into a fan shape by bringing additional reflectors on the dish into operation. The fan-shaped beam is deflected downwards at a suitable tilt angle and scanning continues to cover the ground area ahead. At high altitudes, a mapping display can be produced merely by tilting down the pencil beam to an angle where it will scan the ground.

The quality of the map display produced depends very much on the nature of the terrain. Coastlines give the best and most recognisable returns. The radar energy striking the land features produces strong reflections, while that striking the sea at an angle is mostly reflected away forward of the aircraft. The sea area therefore shows dark on the screen in sharp contrast to the bright display of the land area. Islands can be clearly seen and provide good landmarks. Lakes appear as dark areas but must be treated with caution because mountains also produce dark areas on the screen. While mountains give bright displays, they stop all radar energy and so leave radar 'shadows' at the rear. These could be misinterpreted as lakes, making map recognition very confusing.

The weather radar mapping facility is not usable as a means of navigation but can serve to confirm the aircraft's position as determined by the main navigation systems. With certain modifications it could also be used in zero visibilities to stare ahead and confirm that the automatic landing system really is aiming the aircraft at a real runway. It is, of course, and it certainly knows it is, but the completely independent check by radar is excellent pilot reassurance.

The radar scanner is covered by a dome-shaped construction of a fibreglass material which forms part of the aircraft's nose. This is called a radome as it is transparent to radar energy. In most cases, the radome is finished with a black coating but, where appearances are important, special paints are used to match the aircraft's colour scheme. Thin strips of metal embedded in the

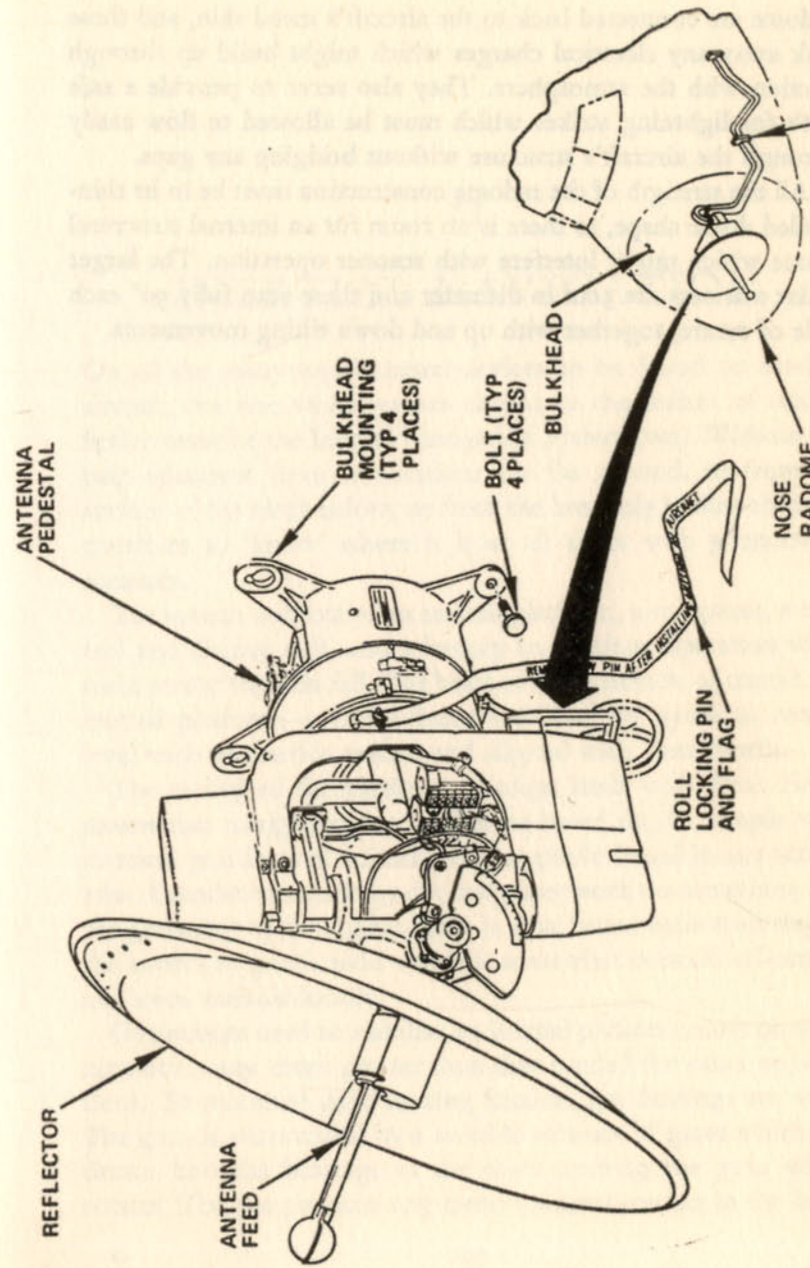


Figure 35 The radar antenna installed in the nose of the Tristar aircraft. The waveguide feeds the radar energy to the scanning antenna which can be tilted up or down by the pilot

radome are connected back to the aircraft's metal skin, and these leak away any electrical charges which might build up through friction with the atmosphere. They also serve to provide a safe path for lightning strikes which must be allowed to flow easily through the aircraft's structure without bridging any gaps.

All the strength of the radome construction must be in its thin-walled dome shape, as there is no room for an internal structural frame which might interfere with scanner operation. The larger radar scanners are 30in in diameter and these scan fully 90° each side of centre, together with up and down tilting movements.

11

INERTIAL NAVIGATION

Of all the many sophisticated devices to be found on modern aircraft, the one which comes closest to the realms of science fiction must be the Inertial Navigation System (INS). Without any help whatever from installations on the ground, or from the surface of the earth below, or from the heavenly bodies above, it contrives to 'know' where it is at all times with phenomenal accuracy.

The system consists of an inertial platform, a computer, a control and display unit, and a battery to continue operation when main power supplies fail. The heart of the system is, of course, the inertial platform—a metal frame stabilised by gyros to remain level with the earth's surface and aligned with True North.

The ability of the platform to align itself with True North means that navigation can readily be based on the simple symmetrical grid lines of latitude and longitude found in any school atlas. Calculations made by the computer work on something like the geometry of the sphere. This is a far better basis than that of the earth's magnetic field which is somewhat twisted, off-centre, and even variable locally.

Gyroscopes used to stabilise an inertial plaftorm must be of an accuracy many times greater than that needed for other applications. To minimise gyro bearing friction, gas bearings are used. The gyro is surrounded by a suitable mixture of gases which are drawn into the bearings as the shaft carrying the gyro wheel rotates. The gas prevents any metal-to-metal contact in the bear-

ings except when the gyro is starting or stopping. In fact, the useful life of such a gyro depends on how often it is started and stopped. The gas-filled container of the gyro may be floated in a liquid which will make it just buoyant so that it does not bear heavily on its support pivots. Some platforms use three gyros; others only two. The number depends on the type of gyro chosen.

The purpose of the stabilised platform is to provide a level base on which two accelerometers can be mounted. An accelerometer is a pendulum (or a weight on a spring) whose movement due to acceleration of the craft can be accurately measured. The two are set at right angles to each other. When the platform is aligned in azimuth to True North, one accelerometer is lined up North-South and the other East-West. The platform system can then measure aircraft accelerations in these two lines of direction. The computer, by combining the two measurements, can determine the actual direction in which the aircraft is accelerating and by how much.

From the acceleration, the computer can calculate the aircraft's speed and the distance it has travelled. When the aircraft stops accelerating and merely continues to fly at a steady speed, the accelerometers will tell nothing but the computer remembers the speed last reached and will happily assume that the aircraft is still travelling at that speed and in that direction until the accelerometers inform it of any change. The computer needs the help of a very accurate clock to enable it to calculate the distance travelled, and this is included in the system.

The part of the inertial navigation system which can be seen on the flightdeck is the control and display unit (Fig 36). The display on this unit is seen as three windows in which various illuminated numbers appear according to the type of information selected. In its most popular role, the two upper windows are displaying the aircraft's position in longitude on the left and in latitude on the right. As the aircraft moves across the earth, the readings will continually change so that they follow its progress and indicate its position at all times.

There is one important requirement which must be met before

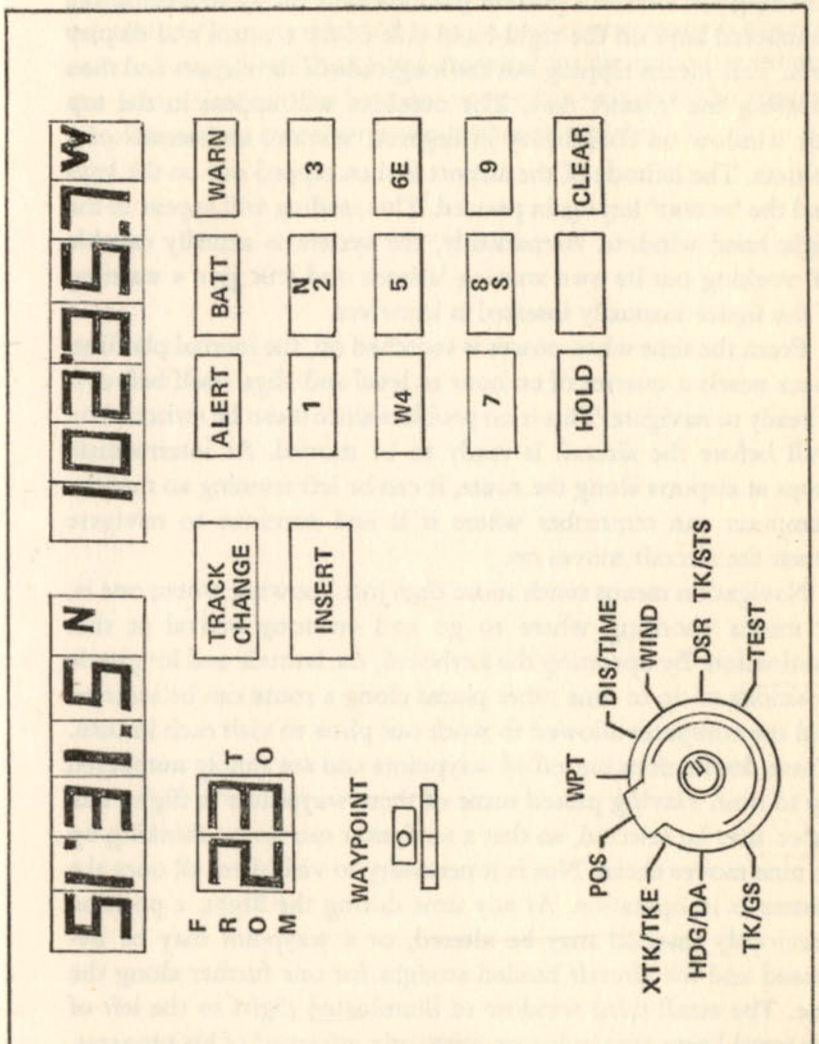


Figure 36 Inertial navigation control and display unit. The numbers in the windows at the top of the unit change to indicate the latitude and longitude of the aircraft at all times. Alternatively, other read-outs can be selected, such as groundspeed, wind speed and direction etc

such a service can be supplied. When power is first switched on to the system, it must be 'told' exactly where it is. This is done by inserting the aircraft's present position into the system using the numbered keys on the right-hand side of the control and display unit. This means tapping out the longitude of the airport and then pressing the 'INSERT' key. The numbers will appear in the top left window on the display in degrees, minutes and tenths of a minute. The latitude of the airport is then tapped out on the keys and the 'INSERT' key again pressed. This reading will appear in the right-hand window. Remarkably, the system is actually capable of working out its own starting latitude and will give a warning if the figure manually inserted is incorrect.

From the time when power is switched on, the inertial platform takes nearly a quarter of an hour to level and align itself before it is ready to navigate. This is no problem since it can be switched on well before the aircraft is ready to be moved. At intermediate stops at airports along the route, it can be left running so that the computer can remember where it is and continue to navigate when the aircraft moves on.

Navigation means much more than just knowing where one is. It means choosing where to go and ensuring arrival at that destination. By operating the keyboard, the latitude and longitude positions of up to nine other places along a route can be inserted and the computer allowed to work out plans to visit each in turn. These destinations are called waypoints and are simply numbered up to nine. Having passed some of these waypoints in flight, still more may be selected, so that a navigator can go on thinking up to nine moves ahead. Nor is it necessary to visit them all once the system is in operation. At any time during the flight, a position previously inserted may be altered, or a waypoint may be by-passed and the aircraft headed straight for one further along the line. The small third window of illuminated digits to the left of the panel keeps the navigator constantly informed of his progress. The first digit tells him the number of the waypoint FROM which he has moved and the second tells him the number of the way point TO which he is travelling. At the same time the upper

windows are continually changing to give the latitude and longitude of the aircraft's position throughout the flight. As each waypoint is approached, an 'ALERT' lamp lights and the aircraft, under control of the autopilot, will turn on to a course towards the next selected waypoint. The course arranged by the computer follows the Great Circle route between waypoints, which is the shortest possible way to travel over the surface of a globe.

12

THE AUTOLAND AGE

By Captain R. E. Gillman,

DFC, DFM, FRMetS, AFRAeS, MRIN

SINCE a large section of the aircraft industry is concentrating on the sophistication of autopilots and the perfecting of automatic landing systems, it might well be asked if present-day civil aircraft are becoming too difficult for a human pilot to fly.

The short answer is 'Yes'—if they are to be flown in such weather conditions as will result in the standards of regularity with safety demanded of the modern airline.

In order to understand how this has come about, it may be helpful to go back some twenty-five years in time, to the point where civil flying recommenced after World War II.

British types of civil aircraft then operating were the de Havilland 89, the Avro XIX, and the de Havilland 86. This latter type was a four-engined biplane which was known as 'Express' airliner, because it could cruise at 120 miles an hour and had an approach speed in the region of 60 knots.

The method of letting-down in bad weather involved the use of a direction-finding station on the ground. The radio operator in the aircraft using the morse code and W/T transmission, signalled to the ground station—'QDM IMI', and then held his key down for 10 to 15 seconds. The ground station took a bearing and relayed this back to the aircraft, also in morse. The pilot used a string of these bearings to make good a track to the ground station.

As the station was approached and the signals became ambiguous, the ground operator put his head out of the window, and using the very efficient direction-finders that nature had obligingly fitted either side of his head, estimated when the aircraft noise was directly above and then, rushing back to his key, he sent the message 'Motors Over'. The pilot then started his stop-watch and began a timed descent while flying a tear-drop pattern with the aid of further bearings which he hoped would bring him to a point near the airfield boundary from which he could effect a landing. Crude as it was, this method enabled landings to be made in visibilities of 100 metres, and the resulting regularity factor was many times higher than it is today.

By 1947, the first of the new British post-war civil aircraft appeared in the form of the Vickers Viking, having an approach speed some 50 per cent higher, and with it came the establishment of the standard beam approach equipment at most of the major airfields.

In this, the ground station originated a signal pattern which resulted in a steady radio beam being projected along the extended centre-line of the runway and a steady stream of dots on its left and dashes on its right. By listening to the signal pattern, the pilot could tell when he had moved away from the desired approach path, but there was still no accurate glide path guidance. And even with the more accurate control in azimuth which resulted, the higher approach speed and less forgiving nature of the aircraft meant that landings in less than 200 metres runway visual range could not be made safely.

In the early 1950s came the Elizabethan and the Viscount aircraft, with approach speeds in excess of 100 miles an hour and integrated flight-director systems that simplified the pilot's task to some extent.

On the ground, the Instrument Landing System (ILS) was being installed. This transmitted a signal in the form of a cardioid diagram, the lobes of which overlapped along the extended centre-line of the runway to give an equi-signal. The equipment in the aircraft sensed the phase relationship of the signals being received

and presented the answer to the pilot on an ILS deviation indicator having a needle pivoted at the top of its face which swung across the centre dot. A second needle at the side swung up and down to indicate deviations from a second beam which was projected up into the air to delineate the safe descent path.

Despite the marked improvement in ground equipment and aircraft instrumentation, minimum runway visual ranges in which landings could be made moved up to 350 metres, due mainly to the reduced time interval between visual contact and the touchdown point at the higher approach speeds.

The 1960s saw the introduction of turbojet aircraft having more critical handling characteristics on the approach, and speeds of 150 knots at this stage, with the result that the authorities set the minimum runway visual range in which a visual landing could be attempted to 600 metres. Thus, in twenty-five years, the minimum visibility in which a landing could be attempted with the requisite level of safety had increased by 500 per cent.

Wherein, then, lie the difficulties?

A well-trained instrument pilot in current flying practice should be able to fly an aircraft down the ILS beam to a decision height of 200ft with acceptable accuracy. At this point, however, he has to look up from his instrument panel and out at visual cues degraded by reduced visibility. From this sort of height, he has fifteen seconds in which to re-focus his eyes from 30in to infinity, identify his position in relation to the centre-line and the glide path, and to initiate and complete corrective manoeuvres before reaching the ground.

Providing that the aircraft is fairly well placed when it breaks cloud this can be done, but with decision heights associated with lower cloud bases or in lesser visibilities the time element becomes critical. It would no longer be prudent to keep the human pilot 'in the loop'—some other technique was needed if airlines were to enjoy improved regularity without any drop in the levels of safety.

This problem was anticipated some twelve years ago when the Hawker-Siddeley Trident was laid down. It was to be the first

civil aircraft in the world having an autoland capability. The idea was to feed the beam signals into the autopilot which would then 'lock on' to the ILS, and during the final stage of the approach, using a radio altimeter, the aircraft's vertical speed would be progressively reduced until touchdown.

However, if the pilot was to be asked to hand over control of the aircraft to a machine when the weather conditions were beyond him, he would need to be satisfied as to the level of integrity of that equipment and to be assured that no single technical failure would be catastrophic.

After much thought and experiment, it was decided that the autopilot would be in 'triplex', that is, three autopilots operating in parallel with comparator circuits between the channels. If one channel said something different to the other two, it would be rejected, a cautionary warning would show on the flightdeck, but the aircraft would continue with its flight path undisturbed on the other two. However, if a second channel failed, then the autopilot would disconnect and the pilot would have to revert to manual flight. If the weather minima at the time were below the manual limits, then a diversion would be necessary.

In order to prove that an acceptable level of integrity could be expected from the equipment, a massive programme of research and development was embarked upon during which automatic landings were carried out in good weather while the performance of the aircraft was monitored by a flight recorder. This device samples a number of parameters throughout the flight and records them continuously on wire or tape. After landing, the record is taken off the aircraft and run through a computer, which then produces a digital or graphical read-out. From this it can be seen where a malfunction occurred and remedial action taken.

The development programme on the Trident has now been running for seven years and has cost as many millions of pounds, but during this time some 20,000 autolands have been completed successfully, and in 1965 this aircraft, with its Smith's autopilot, made the world's first automatic landing with passengers on board in good weather.

The fidelity of this equipment has now been proved so conclusively that British European Airways have become the first airline cleared to operate down to weather minima of 300yd runway visual range using automatics. The airline recorded its first operational automatic landing in this visibility on 30 December 1972, when a Trident 3 was forced by weather conditions to turn back from Paris and return to London's Heathrow airport.

But let us put this in practical terms and follow the course of an airliner entering a terminal area. The autopilot is used throughout flight and is held on course by heading-error signals. The pilot sets up a desired heading on the electro-magnetic compass and the autopilot, sensing the difference between this and the aircraft's actual heading, puts the aircraft into a turn to achieve the desired course. As this is approached, the autopilot rolls the aircraft out on to the new heading and 'locks-on'. The height at this stage, is being held by a 'height lock'. This senses the variations of the machine's height from that demanded by the pilot and smoothly flies it back to the correct level.

When the aircraft is cleared to descend into the control zone, the 'Speed Lock' is pulled. This causes the 'Height Lock' to drop off, and the pitch inputs are now used to fly the aircraft at a constant speed. The pilot reduces the engine power, and in pitching down gently to maintain the speed the autopilot initiates a descent.

The new height to which the aircraft has been cleared is now dialled into the 'Height Acquire' read-out, and the 'Height Acquire Lock' pulled. As the cleared height is approached, computers in the autopilot initiate pitch inputs which flare the aircraft and lock it on to the new height. The pilot adjusts the power to give the speed he requires.

A further refinement is the provision of an auto-thrust control. The pilot having engaged this, speed error signals derived from the indicated airspeed and the air data computer cause the throttles to move backward or forward to maintain the dialled speed.

A further manometric lock is the 'Descent, or Vertical Speed Lock'. This can be selected and a rate of descent set in. The air-

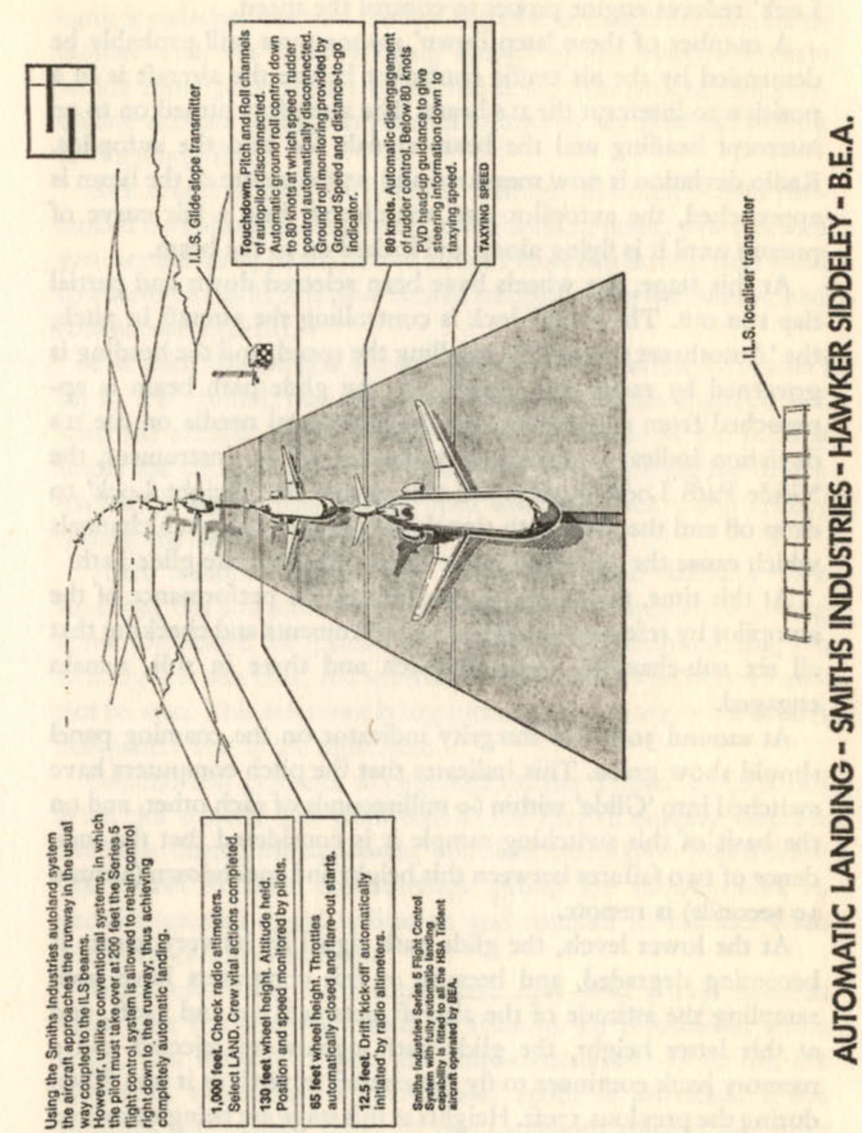


Figure 37 Diagram of an automatic landing

craft now pitches down to achieve this and the 'Autothrust Lock' reduces engine power to control the speed.

A number of these 'step down' manoeuvres will probably be demanded by the air traffic controller before the aircraft is in a position to intercept the ILS beam. The aircraft is turned on to an intercept heading and the beam signals fed into the autopilot. Radio deviation is now measured and, as the centre of the beam is approached, the autopilot puts the aircraft into a fair curve of pursuit until it is flying along and locked on to the beam.

At this stage, the wheels have been selected down and partial flap run out. The height lock is controlling the aircraft in pitch, the 'Autothrust Control' is handling the speed, and the heading is governed by radio rate signals. As the glide path beam is approached from underneath and the horizontal needle on the ILS deviation indicator moves down the face of the instrument, the 'Glide Path Lock' is engaged; this causes the 'Height Lock' to drop off and the glide path signals are fed into the pitch channels which cause the aircraft to nose down onto the safe glide path.

At this time, the pilots are monitoring the performance of the autopilot by reference to their own instruments and checking that all six sub-channels, three in pitch and three in roll, remain engaged.

At around 300ft the integrity indicator on the coaming panel should show green. This indicates that the pitch computers have switched into 'Glide' within 60 milliseconds of each other, and on the basis of this switching sample it is considered that the incidence of two failures between this height and touchdown (around 30 seconds) is remote.

At the lower levels, the glide path signal by its very nature is becoming degraded, and because of this computers have been sampling the attitude of the aircraft between 300 and 130ft, and at this latter height, the glide path signals are rejected and a memory bank continues to fly the aircraft in pitch as it was flown during the previous 170ft. Heights at this stage are being measured by three radio altimeters, working in parallel and compared by monitoring circuits.

At a height of 65ft, the 'attitude hold' phase ends, the memory bank is switched out and the landing flare commences, the rate of closure with the runway being sensed by the radio altimeters which cause pitch inputs to lift the nose, thus progressively reducing the rate of sink to practically zero by the time the aircraft is at ground level.

At a height of 12ft, the flare law changes. Heading is now controlled by radio rate, radio deviation, heading error, yaw rate and yaw acceleration, so that if the aircraft has been nosing into wind to counteract drift it is now turned straight along the runway and touchdown effected.

The pilot disconnects the autopilot and pushes the nosewheel on to the ground, but the rudder channels remain engaged and keep the aircraft rolling straight down the centre of the runway under the control of the ILS signals, the pilot applying the brakes manually, the engines having been throttled back automatically during the landing stage.

Three hundred metres may sound like good visibility to a motorist, but to a pilot who, in a Boeing 747 for instance, is sitting some 30ft above the ground and travelling at 140mph during the landing it is minimal, and certainly the far end of the runway cannot be seen. This reference is important if he is to apply the brakes adequately and at the right time.

Ground roll guidance is provided on the Trident by pick-offs from the wheels. The pilot sets in the known landing distance available during the approach, and after touchdown pulses from one wheel in each undercarriage group are differentiated to provide ground speed indication and counted to subtract from the distance-to-go read-out.

When evaluating such equipment, one must always keep in mind that the pilot may wish to abandon an autoland at a late stage, and because of this an 'Auto-overshoot', or to use the American vernacular, a 'Go-around' mode is provided. If the throttles are pushed open to the maximum manual authority limits, a nose-up pitch input will result, the 'Autothrust Lock' will switch to 'Speed', the ILS signals will drop off and be re-

placed by a wings level signal. The total result is that the vertical speed will be checked, the aircraft put into a climb straight ahead and locked on to 'Speed'.

The decision height chosen to go with the 300 metre visibility minima in the Trident is 12ft. This sounds foolhardy until one realises that during the final landing stage the nose is high in the air and the rate of sink at a minimum, thus the application of full power results in an immediate climb. Many hundreds of auto-overshoots have been carried out during the development trials without the aircraft's wheel touching the ground, and it has been found that, as the autopilot has the aircraft perfectly trimmed, if it is switched out at this stage the average airline pilot has no difficulty in climbing the aircraft away manually by reference to his instruments.

The American aircraft industry has come to the autoland scene only recently with the introduction of the Boeing 747, DC 10 and the Lockheed L–1011, and instead of using the triplex method of achieving the necessary redundancy, they have gone for a 'dual-dual' system. This involves having two autopilots with two channels each and, instead of using comparator circuits between them, they favour in-line monitoring. Their philosophy on ground roll guidance differs, too, in that should the pilot have to revert to manual control after touchdown, he will use ILS guidance through the normal flight director instrument, and no ground-speed and distance-to-go read-outs are available.

These will be essential if landing minima are to be reduced to less than 300 metres, unless automatic braking is available. In this, the pilot sets in the landing distance during the approach and, after touchdown, applies the brakes fully. Computers then modify the brake pressure actually applied to the wheels in order to achieve a smooth deceleration to an acceptable turn-off speed. This idea is still in its infancy, but if one is ever to have a 'zero zero' visibility capability, then the pilot is likely to want a read-out to monitor the efficiency of the automatic braking system.

It is not much use being able to land in very low visibilities, of course, unless one can take-off in similar conditions, but here the

problem is much simplified for the pilot can start from a known position which he can check visually, at least in fog no worse than 100 metres.

The L–1011 already has an automatic take-off facility, the heading being controlled by heading-error signals and pitch demands which call for the optimum rate of rotation at unstick and the correct climb-out attitude. Once airborne, the roll channel receives a 'wings-level' signal.

In view of all the foregoing, one may well ask 'when will human pilots be redundant?' Not in this century, in this writer's opinion. The psychological objections are daunting enough but, in any case, the monitoring of an automatic system is demanding indeed. A deep technical knowledge is desirable and reactions to a technical failure must be fast and accurate. Flightdeck procedures must become more precise as aircraft are flown to lower limits, for there is no time for discussion, but, undoubtedly, safety levels are improving with the advent of automatic flight and from now on airline regularity should improve and the steady increase in landing minima over the past twenty-five years be reversed at last.

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INDEX

Accelerometer, 106
Air Data Computer, 59
Airspeed Indicator (ASI), 9, 47
  True (TAS), 52
Airways, 43
Altimeter, 10, 11, 56
Altitude, 57
Angle-of-Attack, 51
Apparent Wander, 39
Artificial Horizon, 21, 82
Atmosphere, Properties of, 51
Attitude Indicator, 24
Autoland, 113
Automatic Flight Control Systems, 16
Autopilot, 87
Auto-Thrust Control, 114

Basic-Six, 12, 13
Basic-T, 12, 13, 20
Boeing 747, 117, 118

Capsule, 48
  Absolute, 59
  Controlled Leak, 67
Comet, De Havilland, 93
Compass, Magnetic, 37
  Swing, 43
  System, 38
Concorde, 20, 59, 90, 93
Contour Mode, 100
Control Column, 87, 88, 90

DC 10 Aircraft, 118
Decision Speed, 50
Decision Height, 112
Density of the Air, 51
Detector Unit, Compass, 41
Deviation Card, 43
Doolittle, Lt James, 11
Dynamic Pressure Q, 49, 51

Error Signal, 80
Étevé, Capt A., 9

Flare, 64, 117
Flight Director, 78, 88
Flight Level, 59
Flight Simulator, 19
Flux Valve or Gate, 41

Gimbals, 25
Glide Path Lock, 116
Go-Around Mode, 117
Great Circle Route, 109
Ground Mapping, 102
Gyroscope,
  Azimuth, 39
  Directional (DG), 39
  Displacement, 25

Gyroscope—cont.
Inertial Platform, 105
Rate, 31
Toppled, 26

Heading, Magnetic, 37
Height Lock, 114
Horizon Director Indicator (HDI), 24
Horizontal Situation Indicator (HSI), 37, 43

Incidence, 51
Indicated Airspeed (IAS), 52
Inertial Navigation System (INS), 105
Instrument Landing System (ILS), 86, 111
Integrated Flight Systems, 16

Knots, 47

Lockheed L-1011, 118, 119

Mach, Ernst, 70
Machmeter, 75
Mach Number, 70
Mercury Level Switch, 25, 41
Millibars, 56

Night Flying, 11

Pitot, Henri, 49
Pitot Pressure, 49
Pitot/Static System, 49, 67, 75
Power Supply Failure Flag, 28
Precession, 26, 29, 41

QFE, 56
QNH, 57

Radar Scanner, 98
Radials, 44
Radio Altimeter, 64, 116
Radio Deviation Bar, 45
Radome, 102
Rate of Climb Indicator (ROC), 65
Rates of Turn, 31, 32
Rotation Speed, 50

Safety Speed, 50
Shock Waves, 52
Side-Slip, 32
Slip Indicator, 32
Sound, Speed of, 73
Speed Lock, 114
Sperry, Lawrence, 10, 91
Stall, 50, 51
Standby Compass, 45
Standby Horizon, 24
Static Pressure, 49
Systems Trainer, 16

Temperature, Air, 51
Testing of Capsule-Operated Indicator, 55
Transition Altitude, 57
Trident Aircraft, 93, 112, 117, 118
Tristar, 20, 93
Tropopause, 73
True North, 105
Turn and Slip Indicator, 29

Vertical Speed Indicator (VSI), 65
VOR Radio Beacons, 43

Waveguide, 98
Waypoints, 108
Weather Radar, 96

Zero Reader, 84

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